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Long-Range Low-Power Soil Water Content Monitoring System for Precision Agriculture

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***Abstract*—World population growth and desertification are increasing the food demand. Food production must increase to ensure food security in the following years. Smart agriculture tries to improve food production thanks to the adoption of electronic sensors to monitor and control fruit and vegetable crops. Another critical point in agriculture is the use of potable water. Precision irrigation strategies can be implemented to reduce water waste and increase crop production. This paper proposes a long-range, low-power sensor node to monitor soil water content. It is possible to place multiple sensor nodes in the field and use the gathered data to determine the most suitable irrigation strategy. The node communicates thanks to the LoRa protocol and it can also be used in remote areas where it is impossible to have an internet connection.**

***Index Terms*—Smart agriculture, precision irrigation, wireless sensors**

I. Introduction

The problem of food security will become a severe issue in the near future. Producing enough food for everyone on the planet will become harder mainly due to world population growth [1] and desertification [2]. Smart agriculture is tackling this issue by integrating the farmers' knowledge with data taken from different sensors. Precision irrigation is one of the most important aspects of smart agriculture. A target plant should be irrigated whenever the water content of the soil where the plant has its roots goes below a critical limit. This happens when the water in the ground that the plant could use easily is used up. If watering is delayed, the crop is undergone to water stress, compromising the yield. On the other hand, if watering happens too early, there is a waste of potable water. For this reason, it is crucial to determine the exact moment to perform an irrigation intervention. There are some methods to evaluate it, for example, the measurement of the water status of the soil through the soil-water retention curve. Other possibilities are the measurement of the water status of the plant itself [3], [4], the evapotranspiration metric method [5], based on mathematical formulas where a water balance is computed, and, finally, the empirical method based on farmers' experience. The former method, evaluating the soil-water retention curve, is optimal, and it requires low-cost sensors that can be buried on the soil. This method needs only two physical quantities: soil matric potential and volumetric water potential. Therefore, this paper proposes an ultra low-power, wireless, battery-powered sensor node for measuring soil water content. Comparable commercial data-loggers, as TBS12B by Tekbox or 3004ML/3006ML Neon by Unidata states, respectively, 5-7 μA and 50 μA as standby current. The proposed design shows a novel approach to reduce standby consumption extending the node's lifetime. Multiple nodes can be placed in the fields to actuate precision irrigation strategies.

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II. Background

As in [6], where a Low Power Wide Area Network (LPWAN) comparison has been discussed, LoRa is a well-established long-range low-power protocol that modulates signals using a proprietary spread spectrum technique in an unlicensed sub-GHz band, as in Europe 868 MHz. The LoRa devices consume a few tens of mW in transmission and allow a 10-15 km of range between the end device and a gateway in rural regions. The gateway is the stakeholder in charge of collecting LoRa packets from every LoRa node in its range.

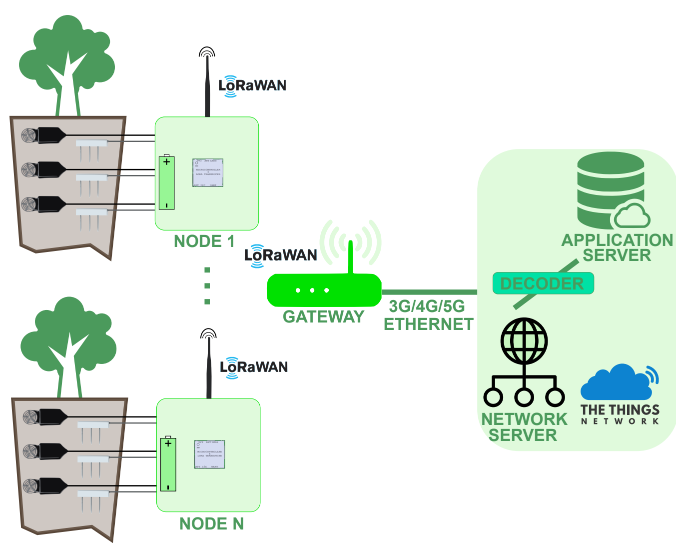

Fig. 1. Designed LoRa architecture water plant monitoring.

The main parameter of LoRa technology is the Data Rate (DR): it is a trade-off between coverage and energy consumed to establish a correct link. For the sake of clarity, a $DR = 0$ is the transmission at the maximum power (and maximum coverage) and, on the contrary, $DR = 7$ is the transmission at the minimum power (and minimum coverage). An important feature is the Adaptive Data Rate (ADR) [7], an embedded algorithm in the LoRa stack firmware. This algorithm optimizes energy consumption based on the distance between node and gateway by setting the correct Data Rate to ensure a good and stable connection consuming as little energy as possible. In this way, when a LoRa device is switched on, the entire initialization step is automatically performed to link to the gateway.

The soil matric potential, being a pressure potential, is typically expressed in kPa. The simplest way to measure it is using a tensiometer. It consists of a porous cup buried into the soil and a tube. The height of filled water in the sensor tube gives a pressure measurement related to the atmospheric one, and therefore the matric potential. Different digital sensors exist to monitor this value [8]. For example, Watermark by Irrometer is a gypsum block where a standard matrix equilibrates with the soil, and its electrical resistance is proportional to the water content of the matrix. Another possibility is exploited in the TEROS sensors manufactured by METER Group, Inc. USA. In this case, a capacitive sensor estimates the water content of a porous ceramic matrix that equilibrates with the soil.

The other key parameter is the volumetric water content (VWC). There are two standard measuring techniques: neutron moisture measurement and dielectric measurement. In the former, an emitting neutron probe evaluates scattered neutrons by the soil based on the water quantity. In the latter, the permittivity is sensed by injecting an AC or DC pulse between two or three electrodes where the soil is the medium in the middle. The VWC is typically expressed as $\mathrm{m}^3/\mathrm{m}^3$, that is, the ratio between the volume of liquid water present in the soil with respect to the soil volume itself. This value is always lower than one, so it is usually expressed as a percentage (%VWC).

III. Proposed Design

The system architecture is depicted in Fig.1. The designed sensor node collects data from sensors and sends them via the LoRa protocol. It is possible to place many nodes in a certain area, as a field, and one gateway connected to the internet. A star topology is realized according to LoRaWAN technology. The gateway will collect the data from all the devices and send them to a LoRa cloud platform to be subsequently analyzed. An arbitrary number of nodes (N) could be connected to the same gateway. The Things Network (TTN) [9], chosen LoRa cloud platform, receives the raw payloads from any registered gateway. Thanks to a decoding application, these payloads are translated into human-readable variables that are then available in the TTN console. The last step is the data storage: The Things Network server could be connected to another service (application server) to save time-stamped and organized data in a comma-separated values (.csv) file.

A novel design of the embedded electronic end-device system is proposed in Fig.2. In run mode, it supplies up to six soil moisture sensors (six channels physically available onboard), and it can read data from them interpreting DDI-Serial protocol data. This protocol uses one single data line to transmit data from the sensor to the microcontroller only. The board is designed to work with two types of soil sensors manufactured by METER Group, Inc. USA: one is the TEROS 11, a dielectric VWC sensor that monitors volumetric water content of the soil and soil temperature. The other is the TEROS 21, a capacitive soil matric potential sensor that provides the soil matric potential and soil temperature. The system can work dynamically from zero to six connected sensors: in this way, it is possible to plug-in any number of sensors satisfying any demand in terms of functionality, precision, or cost for every node. In particular, valuable configurations consider four, five, six sensors placed at various depths in such a way as to determine a sufficiently accurate water retention curve of the target soil. An analogical multiplexing stage is needed to share the unique UART (Universal Asynchronous Receiver-Transmitter) channel of the microcontroller. In addition, an Inter-Integrated Circuit (I^2C) off-board connector is provided to allow the connection with common low-power I^2C sensors as temperature and humidity sensors, light sensors, or pressure sensors. In this way, it is easily possible to correlate soil moisture data with environmental data.

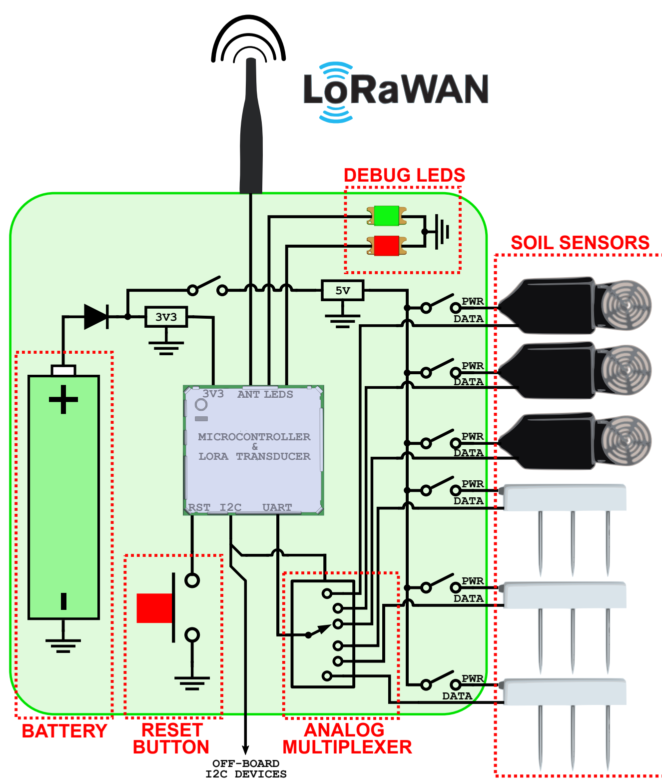

Fig. 2. LoRa plant water monitoring end node overview.

The system is standalone: no supply cables are needed, and one single cell battery is used to guarantee years of lifetime. In particular, the system works with a non-rechargeable Lithium Thionyl Chloride (LiSOCl2) battery [10] that is chosen due to its high capacity, its extraordinary shelf life and wide operating temperature range, making it the best choice for agricultural usages. LoRa protocol is suitable to realize the discussed architecture. Once the data are available in the TTN console, a front-end solution could be developed to store and analyze data properly. Each node stays in run mode only the time needed to read the sensors and send the data to the gateway. After these operations, it will turn in standby mode, and it will be woken up after a configured time. In this way, it is possible to save energy battery, extending lifetime. With the same approach, a power gating stage has been investigated to reduce the main energy-consuming contributions, such as the standby current of soil moisture sensors.

LoRa [11] protocol allows bidirectional communication, so we introduced the possibility to change settings in the nodes over-the-air. It is possible to send a command byte to perform a software reset remotely or change the node's sampling time. The new sampling time is sent in two additional bytes after the command one. On the opposite side, every node sends its data periodically with a dynamic packet: the first byte indicates which channels are connected, and the second byte indicates if requested tasks were performed correctly. For example, a specific bit will be set if the sampling time was modified since the previous command reception. At this point, all remaining appended bytes in the payload are referred to the received data from plugged-in TEROS 11 or TEROS 21 soil moisture sensors. The maximum designed number of bytes for a single payload LoRa packet is 33 bytes, so it is fully compliant with every data rate tier of class-A LoRa systems. The proposed node was implemented on a specifically designed Printed Circuit Board (PCB) (Fig. 3). It is a four-layers PCB to properly handle a radiofrequency stage at $868\,\mathrm{MHz}$. Successively, it was assembled using a Murata CMWX1ZZABZ-078 as the core module where an L0-series ST Microelectronics microcontroller, a LoRa transducer, and needed passive components to correctly bias the RF path, are placed in a single monolithic element. A non-rechargable LiSOCl2 LS14500 battery by SAFT was employed. This is a cylindrical AA size battery that guarantees a nominal capacity of $2600\,\mathrm{mA\,h}$ at $20\,°\mathrm{C}$, an auto-discharge phenomena lesser than 1% per year of storage at $20\,°\mathrm{C}$ and an operating temperature range from $-60\,°\mathrm{C}$ to $85\,°\mathrm{C}$. The analogical multiplexing stage was realized using a MAX4562, an audio/video Integrated Circuit (IC) by Maxim, configured in a specific topology and serially driven in $\mathrm{I^2C}$ protocol. After this, a preliminary characterization was performed: the board was supplied, and two TEROS 21 were plugged-in. In addition, it was connected an off-board PCB on the specific $\mathrm{I^2C}$ connector where an HDC2080 (produced by Texas Instruments) $\mathrm{I^2C}$ temperature and humidity sensor was present.

At this point, the initialization procedure using the Adaptive Data Rate routine set up the node to the greatest data enabling correct communication while consuming as little energy as possible. In our tests, a $DR = 3$ was automatically selected, and a stream of 16-bytes-long payloads appeared on the TTN console periodically. In that payloads, one byte is related to active sensors. One byte corresponds to performed tasks, four bytes are related to air temperature and humidity from HDC2080, and five bytes refers to soil matric potential and soil temperature data for each plugged TEROS 21.

IV. Performance Analysis

A significant factor of an embedded low-power system is the energy consumption: its computation allows predicting a valuable battery lifetime. For this work, a digital multimeter, a Keithley DMM7510, was used to sample current values in each step, both runtime, and standby, as shown in Fig. 4. An

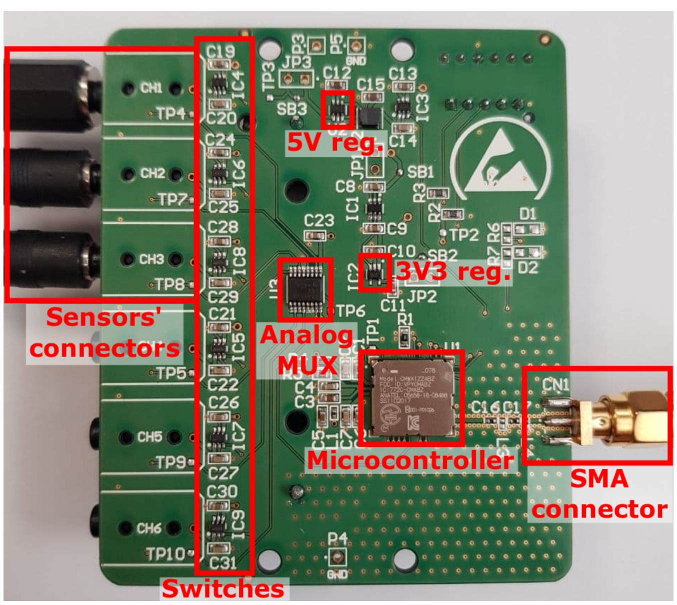

Fig. 3. Top view of designed Printed Circuit Board (PCB).

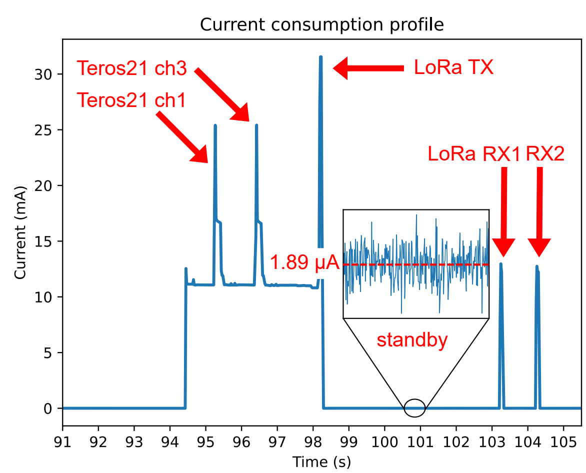

Fig. 4. Current consumption profile.

important value is the runtime current that has an average value equal to $11.0\,\mathrm{mA}$. When the node was sending data via LoRa protocol at 10 dBm, a measured peak current equal to $32.51\,\mathrm{mA}$ occurred.

Finally, an average standby current was measured, and it was equal to $1.89\,\mathrm{\mu A}$, lower than the worst-case computed standby current based on the electronic components' datasheets, $2.65\,\mathrm{\mu A}$. It is possible to note that this order of magnitude of the current is possible thanks to the designed power gating stage: if no switch is placed in the PCB, a total worst-case current of $191.05\,\mathrm{\mu A}$ was computed in case six sensors were connected. In the experimental trial, one complete period (standby time + run time to send one LoRa payload), also called sampling time, was equal to 30 seconds. Approximately 10 seconds were in run time mode, including 5 seconds fixed LoRa transmission/reception window. Tab.I clarifies the obtained results.

Operation	Worst-case peak current	Measured peak current
Standby mode	$2.65\,\mathrm{\mu A}$	$1.89\,\mathrm{\mu A}$
TX	$36\,\mathrm{mA}$	$32.51\,\mathrm{mA}$
RX1	$22.2\,\mathrm{mA}$	$13\,\mathrm{mA}$
RX2	$22.2\,\mathrm{mA}$	$12.7\,\mathrm{mA}$

TABLE I
COMPARISON BETWEEN NOMINAL CONSUMPTION AND EXPERIMENTAL CONSUMPTION OF PCB IN $DR = 3$ WITH A 16 BYTES PAYLOAD LENGTH.

It is possible to note that the standby current is orders of magnitude lower than the run time current. A preliminary simulation of battery lifetime was computed: a possible scenario could be a reference period equal to $1\,\mathrm{h}$ = $3600\,\mathrm{s}$. The experimental energy consumption in run time was computed integrating sensed current multiplied to the nominal voltage $3.6\,\mathrm{V}$ over the time (10 seconds), considering a linear interpolation. The result was $48.5\,\mathrm{\mu W\,h}$. The same consideration was done for the consumed energy in standby mode. Assuming an average value of $1.89\,\mathrm{\mu A}$ multiplied to the nominal voltage $3.6\,\mathrm{V}$ over a span of time equal to $3600\,\mathrm{s}$-$10\,\mathrm{s}$=$3590\,\mathrm{s}$. The result was energy equal to $6.8\,\mathrm{\mu W\,h}$. It is possible to assert that the weight of a few seconds of run time energy is greater than the longer standby energy contribution. In this simulation, it was considered a battery with $1500\,\mathrm{mA\,h}$·$3.6\,\mathrm{V}$=$5400\,\mathrm{mW\,h}$ of energy capacity at $20\,^{\circ}\mathrm{C}$ in a condition where a constant current absorption equal to $40\,\mathrm{mA}$ occurred. This current consumption is close to the LoRa transmission peak current. Moreover, a theoretical battery lifetime equal to 11.15 years was found. This value is heavily affected by working temperature (outdoor usage should consider winter as battery worst case), LoRa Data Rate, and, finally, the sampling time. A realistic figure could be 3-4 years considering a $DR > 0$, a winter condition ($-20\,^{\circ}\mathrm{C}$) and a sampling time equal to $1\,\mathrm{h}$. The last parameter should be carefully chosen: it is easy to demonstrate that, fixing other variables, a sampling time of 30 min approximately halves the lifetime of the system, where instead, a doubled sampling time doubles the lifetime. Moreover, choosing the right sampling time is needed: it is crucial to select a sampling time that allows appreciating whatever changes on the field but avoiding useless measurements that lead to a reduced lifetime.

V. CONCLUSIONS

In this paper, we presented the design of a sensor node to monitor soil water content. The designed node is low-power and can operate without replacing the battery for several years. Furthermore, it is wireless thanks to the LoRa communication protocol, ranging several kms. The sensor node is highly adaptive: it can manage up to six sensors connected simultaneously and can inform the users if a sensor is no longer connected for any reason. The payload message dimensions are dynamically selected depending on the available sensors to reduce the amount of transmitted data. Furthermore, it is possible to send commands to the end node to calibrate the sensors or change some parameters, like the sampling period. Next year, an extensive on-field measurement campaign will be performed after installing multiple nodes directly in fields to monitor the water content and actuate precision irrigation strategies. The final goal is to reduce water waste, performing irrigation only when needed.

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