



**Politecnico
di Torino**

ScuDo

Scuola di Dottorato ~ Doctoral School

WHAT YOU ARE, TAKES YOU FAR

Doctoral Dissertation

Doctoral Program in Electrical, Electronics and Communications Engineering
(38th cycle)

Innovative Leaf Wetness Sensors and LoRa ISM2400 Architectures for IoT Applications

By

Elena Filipescu

Supervisor(s):

Prof. Daniele Trincherò, Supervisor

Dr. Corrado Puligheddu, Co-Supervisor

Doctoral Examination Committee:

Prof. Mirco Raffetto, Referee, Università di Genova

Prof. Giovanna Maria Dimitri, Referee, Università di Milano

Politecnico di Torino

2026

Abstract

Different production sectors, and in particular agriculture, increasingly rely on sensing technologies and communication systems to support precision monitoring, decision making and automation in large-scale outdoor environments. In this context, the availability of compact, low-power and robust sensing devices, combined with reliable long-range wireless communication, plays a key role in scalable Internet of Things (IoT) solutions.

The thesis aims to develop innovative Leaf Wetness Sensors (LWSs) integrated with advanced communication systems for IoT applications. In particular, a capacitive LWS is developed and combined with a communication system based on Long-Range (LoRa) technology, including the possibility to exploit alternative frequency bands and emerging transceiver solutions.

Leaf Wetness Duration (LWD) is a critical parameter for predicting fungal diseases in crops, directly impacting agricultural productivity and sustainability. Traditional approaches rely either on bulky weather stations or on indirect estimation methods based on temperature and humidity measurements. These last ones often fail to capture complex environmental conditions such as rainfall, canopy retention and evapotranspiration effects. To overcome these limitations, a capacitive sensing approach is proposed, exploiting the variation of the dielectric constant of the surrounding medium to directly detect wetness on the sensor surface.

The proposed sensor is implemented as a two-sided, four-layer Printed Circuit Board (PCB), enabling independent measurements of the upper and lower sensing surfaces. A dedicated analytical model based on grounded coplanar waveguide theory was developed: this allows to describe the sensor capacitance as a function of geometry and dielectric properties. The sensing subsystem was interfaced with a Capacitance-to-Digital Converter (CDC), allowing direct digital readout with

reduced circuit complexity and low power consumption. Experimental validation demonstrated reliable and repeatable measurements in controlled environments.

In order to enable field data collection, the sensor was integrated into a Low-Power Wide-Area Network (LP-WAN) architecture based on LoRa and LoRaWAN, using MikroTik gateways (model LtAP 98 LR8 LTE), The Things Network (TTN) as network server and iXemWine platform as application server. In addition to traditional operation in the sub-1 GHz band (e.g., EU868) the communication performance was investigated in the ISM2400 band (2400–2485 MHz), for which, before the current study, limited experimental evidence was available in the scientific literature. Unlike traditional sub-1 GHz LoRa systems, the ISM2400 band offers global availability and no duty-cycle restrictions, enabling more flexible and lower-latency communication. However, higher frequencies introduce challenges such as increased path loss, stronger dependence on Line-of-Sight (LOS) conditions and coexistence with multiple wireless technologies.

Extensive outdoor measurement campaigns were therefore conducted to characterize long-range wireless communication in the ISM2400 band under rural conditions. In particular, Campaign 1 demonstrated the feasibility under LOS conditions, achieving a Packet Delivery Ratio (PDR) of 100% up to 18 km and revealing non-uniform interference across channels. Campaign 2 extended the communication range up to 24.7 km, further confirming the robustness of the communication in favorable propagation conditions. In Campaign 3, a more challenging long-range scenario was investigated, establishing a link of approximately 39 km using a high-gain (18 dBi) directional antenna; although the PDR decreased, the results confirmed the feasibility of extreme-distance communication and highlighted the impact of path loss and environmental variability. Campaign 4 analyzed a multi-node configuration with different spreading factors, confirming the expected trade-off between data rate and reliability. Finally, Campaign 5 evaluated system performance through drive-tests with a vehicle-mounted end-node transmitting geo-referenced data packets, showing reliable communication under LOS conditions and a rapid degradation of the link in the presence of obstructions. This result is not directly related to the application of the LWS, which is typically deployed in a fixed position; however, it opens the way to possible future scenarios in which several types of sensors could be mounted on autonomous mobile vehicles for continuous monitoring of different portions of the fields at different times of the day.

For long-term field deployments, the LWS was integrated into LP-WAN nodes operating in two alternative bands, the EU868 and the ISM2400 bands, as a stand-alone sensing element or in multi-sensor weather stations. A total of 53 installations across 5 Italian regions, representing different pedoclimatic conditions, were involved, demonstrating the scalability and practical applicability of the proposed approach at the territorial scale. In particular, the solution in the ISM2400 band can support quasi-real-time agricultural sensing applications beyond traditional sub-1 GHz duty-cycle limitations. The sensor was able to detect wetness conditions when indirect estimators failed, confirming its effectiveness in real agricultural conditions. Energy characterization and power-management techniques further improved suitability for battery-powered deployments.

Overall, the thesis demonstrates that compact capacitive sensing and long-range wireless communication can be effectively combined to enable scalable monitoring systems for precision agriculture. The proposed LWS provides a robust and field-ready solution for direct leaf wetness monitoring, while the usage of LoRa in the ISM2400 band highlights its potential for real-time IoT systems.