

Combined Physical and Digital Sensor Twin for Monitoring Fresh Fruits in the Cold Chain

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Summary:

The proposed sensor twin design enables easy installation and wireless measurement of fruit quality relevant parameters during cold storage. The system was tested using 11 sensor twins in a 50-ton commercial apple cold room. Comparing dew point and fruit temperature revealed critical conditions leading to condensation on the fruits. Reliable communication was achieved from within the fruit stacks for signal path lengths up to 4 m, with packet losses < 3.5%, signal-to-noise ratio > 5 dB, and signal attenuation of 16 dB/m.

Keywords: LoRa, physical twin, packet losses, cold chain, humidity sensors, LoRaWAN

Background, Motivation and Objective

Maintaining high fruit quality during cold storage and in the logistic chain requires keeping environmental parameters within recommended ranges and continuously tracking of deviations. Direct humidity measurement inside fruit stacks is essential to capture microclimatic conditions that are not represented by ambient air sensors. The temperature difference between fruit surface and surrounding air plays a key role in processes such as water condensation on the fruit, evaporation, mass loss and microbial growth.

Installation of wired probes is mostly not feasible in bins or boxes with fruits under commercial cold chain handling conditions. The performance of LoRa in industrial IoT applications was analyzed in [1] but data for fruit storage environments is still scarce. Wireless communication in such environments suffers from high signal attenuation by the high moisture content of fruits.

Description of the New Method or System

The proposed system combines extended sensing capabilities of a physical twin with its digital counterpart [2] to run prediction algorithms for condensation and mass loss, and later convert these indicators to a prediction of quality risks.

The physical twin mimics a cluster of 4 apples using plastic spheres of 8 cm diameter, filled with a hydrogel material, which provided similar thermal properties to real fruits (Fig. 1). The electronics consist of a Sensirion STS35 sensor for surface temperature of the spheres, SHT45 for air humidity and temperature, and wetness sensors for direct measurement of condensation. The

latter one consists of a finger structure with 0.3 mm spacing on a 0.1 mm thick flexible PCB. Sensor data are processed on a STM32 Nucleo microcontroller and transmitted by a RN2483 LoRa radio. LoRa communication uses different spreading factors (SF). Lower SFs mean longer battery lifetime [3], shorter airtime, but reduced communication range.

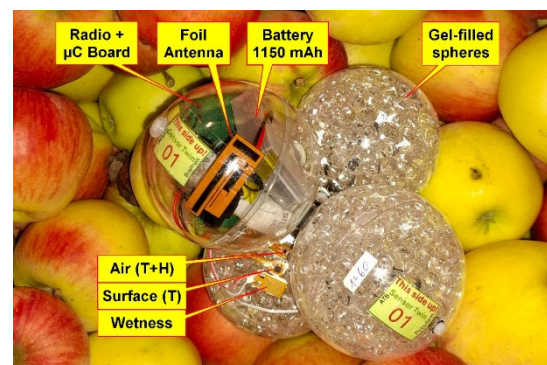


Fig. 1. Physical sensor twin components

The physical twins were placed in apple bins (1.2 m · 1 m · 0.75 m / 300 kg capacity) within the top layer of fruits. A commercial cold storage room was filled with 154 bins, arranged with vertical and horizontal gaps of 0.1 m width between bins. Two LoRa gateways were installed, one under the ceiling and one above the door.

Results

Various types of events, e.g., setpoint changes, can increase the dew point above the fruit surface temperature (Fig. 2). Such dew point under-shoots (DPU) mark the beginning of water condensation on the fruit. In addition to an earlier

analysis of DPUs [4], this contribution focuses on the communication performance of LoRa in fruit cold storage. The 868 MHz band is less affected by fruits compared to standard 2.4 GHz communication [5].

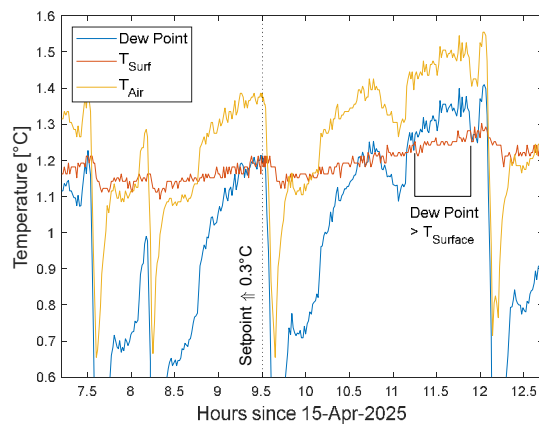


Fig. 2. Dew point rises above surface temperature after set point was increased by 0.3°C. Condensation on fruit surface is expected during the marked period

Signal-to-noise ratio (SNR), radio signal strength indicator (RSSI), packet losses, and sensor battery voltage were read out via The Things Network (TTN). Communication performance was tested for two scenarios: a) fixed SF values from 7 to 11, and b) automated setting of SF by the server.

RSSI is almost independent of SF and mostly depends on the length of the signal path through fruit (SPF). Signal attenuation was measured to 16.5 dB/m (Fig 3). Sensor-J had a higher RSSI due to the free air space at the door side.

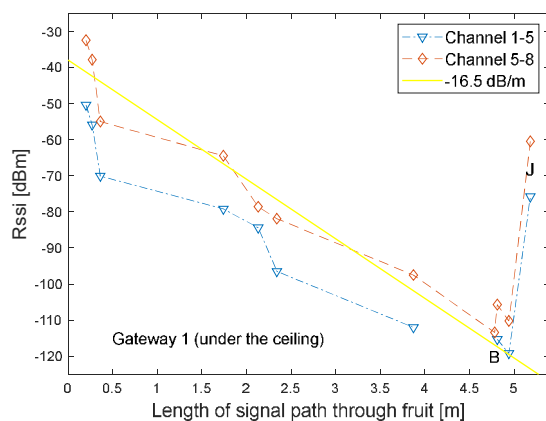


Fig. 3. Drop of signal strength (RSSI) by 16 dB/m

Additionally, a dependency on the radio channel was detected. The receiver implementation on the gateway uses different radio chips resulting in average RSSI that was 13.5 dB higher for channels 6 to 8 compared to channels 1 to 5.

Packet losses remained stable at max. 3.5% for SPF < 4 m. Combining the data of two gateways lowered to packet losses to 1.5%. Radio

transmissions with SF 11 showed higher losses. SF 11 requires 4 times longer airtime than SF 9 and is, therefore, more affected by collisions and by occasional distortions, e.g., the gateway switching from receiver to transmission mode for downlink messages.

SNR drops for SPF > 4 m (Fig. 4). Sensor-B was buried between the apples. It had a 15 dB lower SNR than sensors in the top layer of fruits. Even for the highest SF, the packet losses increased to 14% or 64% for the two gateways.

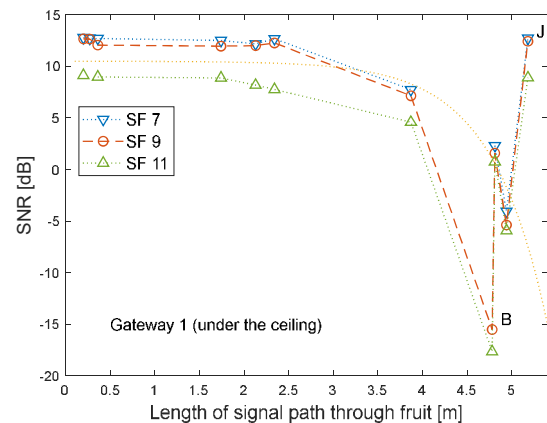


Fig. 4. Signal-to-noise ratio (SNR) for different SF

The theoretical battery life for transmissions in intervals of 150 s was calculated to 10 months. In practice, battery life of only 4 months was achieved due to low temperature conditions. Power consumption can be further reduced by collecting two sensor measurements before transmitting a combined packet.

References

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