Development of a Modular Zigbee/LoRaWAN Wireless Sensor Network for Environmental Monitoring with Biohybrid Sensors

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Abstract

The Watchplant project develops a biohybrid wireless sensor network (WSN) for environmental monitoring. Sensor nodes are exposed to nature and wilderness, making WSNs commonly suffer from node failure and data loss. We propose a novel approach to increase the network's robustness: Using two different communicaion technologies. Zigbee is used for fast, short-range communication of measurement data, and LoRaWAN for slow, long-range communication of configuration messages and error detection. Experiments were conducted with 15 sensor nodes in a controlled lab environment with simulated node failures. The WSN displayed its ability to effectively self-regulate node failures and shows that the heterogeneous communication approach is a viable alternative to conventional WSNs.

1 Introduction

Watchplant [1] is an EU Horizon 2020 project concerned with environmental monitoring for climate change and urban air pollution research. Watchplant develops a novel approach based on a wireless sensor network (WSN) of biohybrid devices, so-called *phytonodes*. Each phytonode consists of a plant with attached electronics. Electrodes are inserted into the plant's stem to read the electrical potential, which changes depending on external stimuli like temperature, light, and wind. These signals are processed with statistical methods, e.g. feature extraction and discriminant analysis, and machine learning methods to classify the triggering stimulus [2]. The proposed setup aims to be a long-lasting, energy-efficient, cheaper alternative to conventional sensor stations.

This paper's contribution is a prototype WSN that was deployed in lab conditions. One single sensor can not give an accurate representation of a larger area like a city. A WSN allows the deployment of multiple sensor nodes evenly distributed over a target area. This is especially important for phytosensors, as a single phytosensor has a higher variance compared to a conventional sensor. As sensor nodes are prone to failure, WSNs have to be developed with robustness in mind. Previous approaches sacrifice bandwith for data messages for network management messages. We develop a heterogeneous WSN using Zigbee and LoRaWAN communication technologies. The hybrid Zigbee/LoRaWAN network provides a novel alternative to WSNs which rely on one communication technology. Based on our literature overview, very little research is done in the area of WSNs with multiple communication technologies. Examples of Zigbee and LoRa combinations are sensor nodes that can switch the technologies, but only after user request [3], and Zigbee and LoRa clusters that communicate over a Zigbee/LoRa bridge [4]. Our goal is to design a network that takes advantage of the strengths of both communication technologies: Zigbee for communication of measurement data, and LoRaWAN for network management. Initial experiments show that our approach to increase the robustness is effective without reducing communication bandwith for network management.

2 Technologies

Wireless Sensor Networks use a variety of communication technologies to transmit data wirelessly. The most commonly used communication technologies in WSNs include Zigbee, Bluetooth Low Energy (BLE), Wi-Fi, and LoRa (Long-Range).

Zigbee [5] is a wireless communication protocol designed for high data rate, low power consumption, and long battery life applications. Zigbee operates in the 2.4 GHz band and uses a mesh networking topology to enable communication between nodes. It is based on the IEEE 802.15.4 standard, which specifies the physical layer and medium access control layer for low-rate wireless personal area networks (LR-WPANs). Zigbee supports a maximum range of up to 100 meters and a maximum network size of 65,536 devices. It is suitable for applications such as smart homes, industrial automation, and building automation. Computer chips that implement Zigbee communication can easily be integrated into smart devices or attached externally using, e.g., an XBee module.

LoRaWAN (Long Range Wide Area Network,[1] is a low-power, long-range wireless communication protocol de-

[1] `https://lora-alliance.org/resource_hub/`

signed for IoT applications. The network topology consists of low-power end devices connected to gateways with internet access. The gateways are connected via a network server back-end like The Things Network (TTN)[2] forming a star-of-stars topology and thus increasing coverage. Using the sub-GHz spectrum, LoRaWAN can provide long-range communication capabilities of up to 10 km in rural areas and 2-3 km in urban environments. However, it has a low data rate (typically in the range of a few kilobits per second).
LoRa (Long Range) [6] is the physical layer technology used in LoRaWAN that provides long-range communication capabilities with low power consumption. LoRa uses chirp spread spectrum modulation, which enables robust communication with low sensitivity to noise and interference.

3 Zigbee/LoRaWAN Hybrid Network

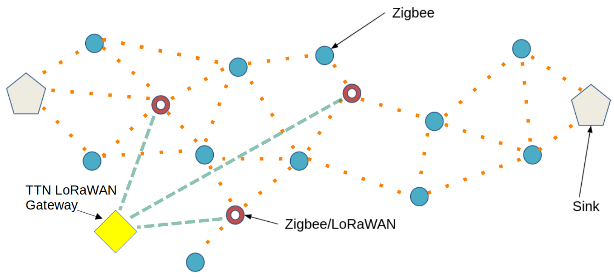

Figure 1: The schematic of the proposed hybrid Zigbee/LoRaWAN network.

For the prototype of our heterogeneous sensor network, we decided to use Zigbee and LoRaWAN. The main differences between these technologies are communication range and bandwidth. Zigbee can transfer data fast over a short range, while LoRa can transmit data slow, but over a far longer range. The network uses the advantages of both technologies and uses Zigbee to transmit measurement data and LoRaWAN to transmit control flow messages. During long-term network deployment, we expect more regular and long data messages, but fewer, shorter control messages. In a bigger network, data messages that are sent via Zigbee do not have the range to be directly transmitted to a data sink. Instead, Zigbee will utilize intermediary nodes for multi-hop routing. This can be problematic if intermediary nodes fail. LoRa, on the other hand, has a far higher range of multiple kilometers. Using the LoRaWAN network, a LoRaWAN node can always directly communicate with a LoRaWAN gateway without dependence on intermediary nodes.
The network design is displayed in Fig. 1. Zigbee nodes collect data and send it via Zigbee to the sink. Zigbee/LoRaWAN nodes do the same, but they also have additional tasks. In contrast to pure Zigbee nodes, they request an acknowledgment from the sink. They count over a fixed period how many messages failed to get through and send the count to the nearest public TTN LoRaWAN gateway. A server-side Python program evaluates the data and, if necessary, changes the network configuration. The behavior of Zigbee and Zigbee/LoRaWAN nodes is summarized in Fig. 2 and 3.
For example, if only one of the LoRaWAN nodes reports failed messages, the Python controller can assume that the network is damaged, but also that the damage is contained in a relatively small area, i.e., the Zigbee/LoRaWAN node itself or a few intermediary Zigbee nodes. The majority of the network (majority of Zigbee nodes and also the sink) is still intact. Otherwise, more Zigbee/LoRaWAN nodes would have reported failed transmissions. As long as the majority of the network is still operating, there is no need to react and change the configuration. The controller can also be used to send out a notification to the operators running the network (via email) to fix the broken nodes.
A bigger problem is a failing data sink because the network loses all data from all nodes. In this case, a majority of Zigbee/LoRaWAN nodes report failed transmissions. Now the controller reacts and sends out a new network address to change the data flow to the backup sink. The Zigbee/LoRaWAN nodes receive the new address as a LoRaWAN message and reconfigure their sink addresses. Then they broadcast the change to all Zigbee nodes in the network. In this way, only a small portion of the information is lost.
Additionally, the operators can use the controller to change network settings remotely. We implemented changing the measurement frequency of all nodes, but there are more possibilities depending on the sensor loadout and the requirements.

3.1 Zigbee Node

The Zigbee node is the base of a sensor node. It has only Zigbee communication capabilities through the use of the attached XBee module. We use STM32WB55 NUCLEO boards and USB dongles for processing the data. For the power supply, we use a solar power manager board DFR0559 from DFRobot connected to a 1500 mAh battery and a solar panel.

3.2 Zigbee/LoRaWAN Node

Zigbee/LoRaWAN nodes are extensions of Zigbee nodes. They do the same task - measuring data and sending it to the sink. In addition to their XBee modules, they also have LoRa modules for LoRaWAN communication. They periodically send LoRaWAN messages over the nearest LoRaWAN gateway to the server. Using Zigbee/LoRaWAN nodes with TTN allows the use of any connected community gateway. In this way, the whole network is easier to

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[2]https://www.thethingsnetwork.org/

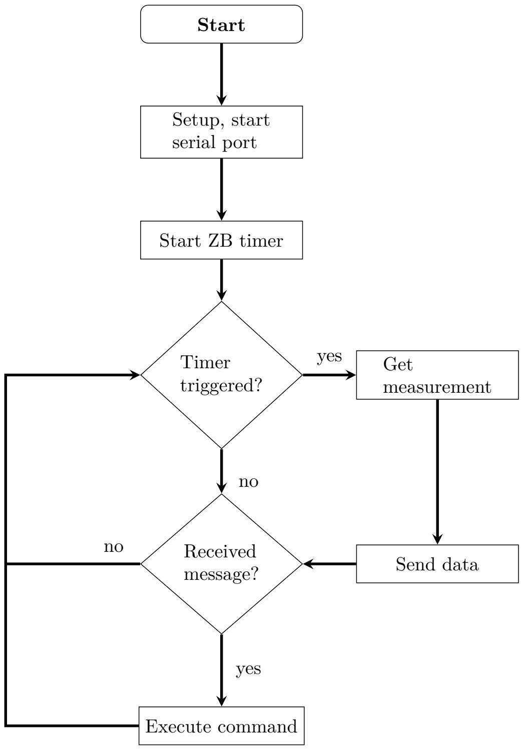

Figure 2: Flowchart explaining the operation of Zigbee nodes.

deploy because it can use public infrastructure for communication. The used hardware consists of a Heltec Wireless Stick v2.1, which includes a LoRa module, and a connected XBee. These devices are also powered by a battery and a solar panel.

3.3 Data sink

The primary sink used in the experiment was the custom-made, waterproof, autonomous data acquisition unit called the Orange Box. The main processing unit inside the box is a Linux-based mini-computer Rock Pi S, similar to the Raspberry Pi. The second sink was built out of a Raspberry Pi 4 and an XBee module. Every device that can interface with an XBee can be used as a sink. However, the program of the sink uses Python and relies on a conventional file system, so it is recommended to use mini-computers instead of microcontrollers. The program on the sink listens to the data and creates new folders and files for each transmitting sensor node. The names of the files are based on the 64-bit MAC addresses of the XBee modules.

3.4 LoRaWAN Controller

Using LoRaWAN and TTN, the Zigbee/LoRaWAN nodes send their status messages to the nearest TTN gateway. The controller downloads the messages from the TTN server. This requires that the controller code is running on a device that has internet access. The controller is used for periodically checking the network status and sending user commands.

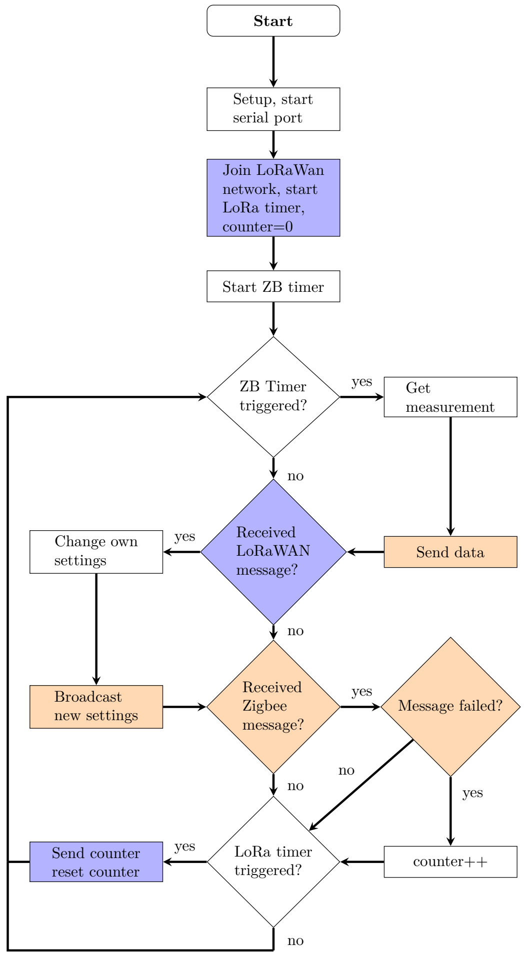

Figure 3: Flowchart explaining the operation of Zigbee/LoRaWAN nodes. Blue nodes highlight LoRaWAN communication, while orange nodes highlight Zigbee communication.

To check the network status, it relies on received messages that notify the controller about failed transmissions between Zigbee/LoRaWAN nodes and the sink. In our practical test, we used three Zigbee/LoRaWAN nodes. In this scenario, the controller implements the following rule: "If the majority of Zigbee/LoRaWAN nodes report one or more failed transmissions, the sink has failed." The controller then sends a LoRaWAN message back to the network containing an alternative sink address. The controller cycles through all known link addresses if a change is necessary. Selecting a good threshold of failed transmissions and reporting devices is a design decision and depends on the size and the structure of the network. In general, some messages can be expected to fail. The second task of the controller is to react to human input. An operator working with the network might want to change network settings, like the measurement frequency of the sensor nodes. This is possible over the internet using the controller, so that the network can be controlled and monitored worldwide, as long as the operator has internet access. Depending on the task the network should perform, a multitude of options can easily be added to the system.

4 Results and Discussion

In the laboratory test setup shown in Fig. 4, we used 15 devices: two sinks, three Zigbee/LoRaWAN nodes, and ten Zigbee nodes. Failures of the sink and other nodes were simulated by disconnecting their XBee modules, effectively disabling their communication. In our experiments, the network fulfilled the set expectations and proved that our heterogeneous networking concept has great potential for further development and future use in the project. The network can transmit messages as fast as a native Zigbee network but has more reliability and robustness. In contrast to other approaches for increasing the robustness and reliability of WSNs, our network is keeping its performance because it does not need to sacrifice communication bandwidth for network management; this task is performed by LoRaWAN communication. Moreover, the network can be easily extended with additional types of devices. We have developed the code for interfacing with the XBee module for the Arduino framework, Arduino through PlatformIO, MBed OS, and Python. As long as a device can run any of these four options, it is easy to integrate into the network.

Figure 4: Test network with 15 nodes: Two sinks (RPi on the left side, open Orange Box on the right side), three Zigbee/LoRaWAN nodes, and 10 Zigbee nodes.

While the first test was promising, there are still drawbacks to consider. One disadvantage is the increasing cost of sensor nodes: Each additional communication technology adds at minimum a new transceiver. This was especially notable in the prototype stage. A second disadvantage could be the power consumption. The used Heltec Wireless Sticks did not perform as promised by the manufacturer, so we could not do an in-depth investigation of the additional power consumption due to the use of LoRaWAN.

5 Conclusion and Future Work

We developed a heterogeneous Wireless Sensor Network with a hybrid communication system and successfully deployed the prototype in our lab. Due to the use of two different communication technologies, we were able to decouple the infrastructure for sending data messages and the infrastructure for sending status and reconfiguration messages. In a conventional WSN, the sink (base station) has two responsibilities: receiving sensor data and sending out reconfiguration messages when it detects errors. Using two infrastructures, we were able to split these responsibilities so that the LoRaWAN controller is responsible for error detection and reconfiguration, and the sink is used only for data collection. This reduces the bottlenecks in the network and increases overall robustness since the critical roles are distributed to multiple devices. Furthermore, the LoRaWAN range spans multiple kilometers, so as long as there is a gateway close enough, the network can still be monitored and configured even without direct access to the internet.
As a next step, we deploy the prototype in outdoor conditions for a longer time and compare the performance to networks with a single communication technology.

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Authors' Statement

Conflict of interest: Authors state no conflict of interest.

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