A cost-effective and versatile sensor data platform for monitoring and analysis of building services

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ABSTRACT

Conventional building management systems are costly to install in existing buildings. Building services fail, which results in a cascade of incorrect responses, or occupants and administrators misuse systems. A possible way to reduce the installations costs is to use wireless sensor networks (WSN) to monitor and control building services.

Monitoring of building services provides several challenges. Access to the sensor nodes is intermittent and often requires coordination with building administrators or occupants, so the sensor nodes need sufficient battery power to last several months or years.

In this paper we describe a low-power low-cost generic sensor platform that can be configured to sense several variables at each node only by adding the sensors. With the platform, we are able to deploy a high-resolution monitoring system to identify and correct faults with sufficient battery power to last several years.

The paper describes the developed hardware and software package that is used to sense data, transmit them, store them and visualize. The hardware components are without import restrictions to the European Union and all the software is free and open-source. All the choices are discussed and explained in the paper.

One major challenge is that the wireless network must transmit through building materials, such as concrete. Our development weighed the advantages of a low-bandwidth, long-range protocol like LoRaWAN against the advantages of a high-bandwidth, short-range protocol like Nordic nRF24L01+ or Zigbee, which may require several repeaters. Another challenge that was handled is security and encryption.

As such, the platform focuses on digital sensors that meet performance criteria, such as power consumption, stability, precision and accuracy.

KEYWORDS

Wireless sensor networks, monitoring, building services, visualization

1 INTRODUCTION

Consequences of inappropriate building operation are occupant complaints, discomfort and reduced productivity which leads to reduced tenant retention and reduced asset value of the building (Annex 47, 2010). In the USA, as much as 30 % of energy consumed by heating, ventilation and air-conditioning (HVAC) and lighting in commercial buildings results from inadequate monitoring and control (Kim & Katipamula, 2017). This illustrates how expensive malfunctioning HVAC systems can be.

The facility managers are without the appropriate tools to diagnose problems. The Building Management System may indicate that there is a problem, but it is very unlikely to be collecting the necessary forensic data to solve it (Noye et al., 2015).

Wireless sensor networks that operate in parallel or overlaying the BMS data can make high-resolution temporal and spatial data abundantly available (Dong et al., 2010; Painter et al., 2012). Wireless sensor networks (WSN's) are evolving at a very quick pace, yet the state-of - the-art platforms all suffer from different weaknesses like too short range, no versatility, limited sampling rate, proprietary protocols, excessive computing power, costly backend

solutions and recurring fees (Hamilton, 2018; Sigfox, 2018; Disruptive, 2018). The most versatile solution with long-range transmission capability for the built environment that we are aware of is currently the powerful Waspmote platform from Libelium (2018), yet to deploy dozens of sensors in a building, it is quite costly.
This paper presents a versatile sensor platform that can collect data with optimized wireless battery-powered nodes, and be able to transmit data over long distances in the built environment, store data and display them at a minimum cost and with full control of the user.

2 SETUP

The setup relies on hardware components that are exactly suited for the purpose with no excessive computing power and open source software. Figure 1 illustrates schematically the sensor network, the wired and wireless connections and the data management platform based on open source software and services,
Wireless sensor network may have different topologies: either "mesh" or "star" or hybrids. The mesh topology is compelling because the nodes are inter-connected, and act as relay-stations for each other. This increases the likely-hood that data transmissions are received eventhough some nodes malfuntions and principally it expands the range of the sensor network, because the data packet can be passed between multiple nodes before it reaches the gateway. However, the relay-mode does not fit well with long battery life. Some nodes, at least, has to be powered, and experience has shown that to benefit from the mesh, a minimum number of sensors is required and you need to adhere to some minimum distances between the nodes to ensure alternative data transmission lines.
The star topology requires one powered gateway to be in the center of the "star", and if you require extended range in some areas, it is simple to add a powered repeater.

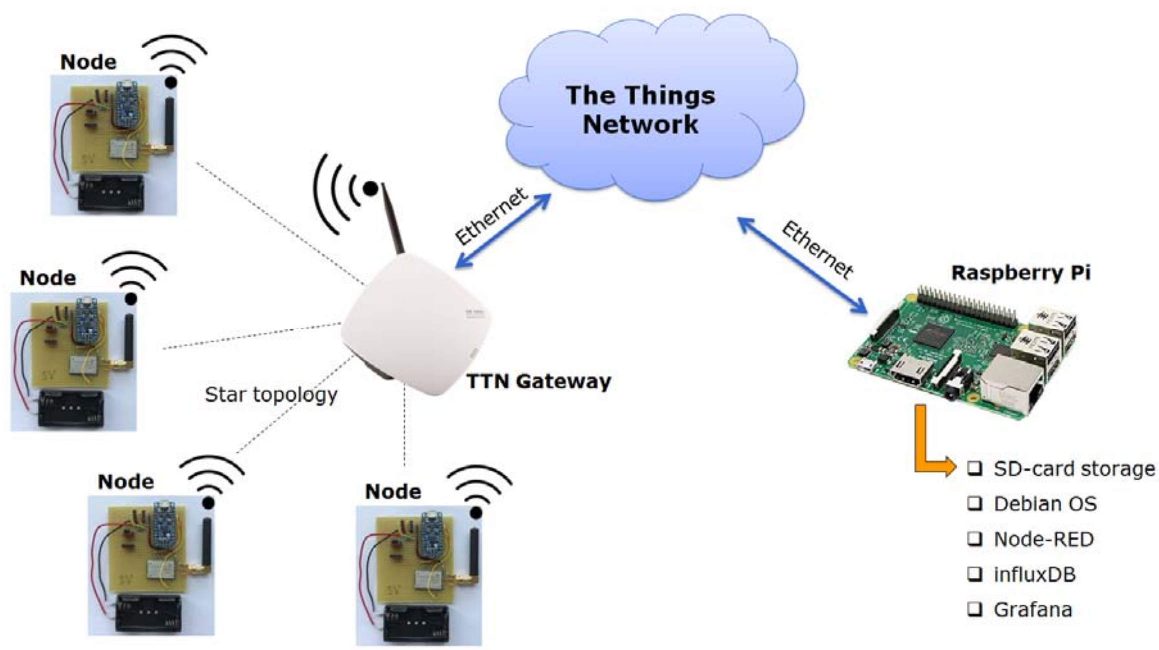

Figure 1: Schematic of the sensor network

2.1 LoRaWAN

LoRaWAN is a Low Power Wide Area Network (LPWAN) that employs the star topology and has end-to-end encryption based on AES128.
In the built environment, concrete walls with rebars are the most hostile type of wall to radio transmitted signals. LoRa modulation is a derivative of the Chirp Spread Spectrum (CSS) modulation, which was originally developed in the 40's for military radars, and has later in history been used in space communication due to its relatively low transmission power requirements and robustness to interference. Thus it is also suitable for the built environment, where multi-path and interference is always the risk.
The LoRa protocol uses a frequency with restrictions. In Europe, this means that the device can only use 1% of the duty cycle. This means that if your transmission air time is 1 second, you have to what 99 seconds before the next transmission. However, in the worst case the air time of a packet of 20 bytes is 1.2 seconds, making it possible to send again after 2 minutes. Thus we consider the low-bandwidth long range LoRaWAN protocol to be superior over 2.4 GHz implementations (Bluetooth, Hamilton, Nordic nRF24L01+, Zigbee and others).

2.2 Nodes

The major components of the nodes are the:

- Arduino-based board (Adafruit Pro Trinket 3.3V) is optimized for size, computing power and memory (2 kB, 70% used max). The Pro Trinket is based on the ATmega328p micro-controller running at 12 MHz
- RN2483 LoRaWan compliant radio module from Microchip for long-range sub-1 GHz transmisson (868 Mhz)
- 1/8 wave length antenna for short, sturdy antenna design rated at 868 MHz
- Some sensor connectors for a versatile platform that accepts different sensors like temperature, humidity, luminosity, radiant temperature, CO2, VOC's, PIR, sensors with extension wires, 3-axis accelerometer, 3-axis magnetometer and more.
- Battery container for two AA or two AAA batteries

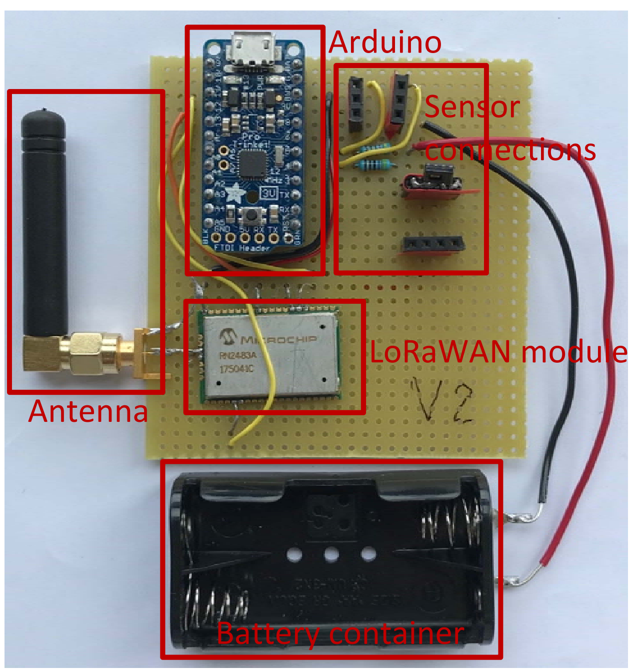

Figure 2: The sensor node with the five different main components

In Figure 3 the wiring of the modules can be seen. SDA and SCL are also marked on the diagram, they are used for the HIH6120 ambient temperature and humidity sensor.
Port 6 on the Pro Trinket is also marked, since this is where the DB18b20+ temperature sensors are connected with their data pin, see paragraph 2.4.

The Adafruit board is modified in two manners:

- The onboard diode (green) emits light when the board is powered, but it uses nearly 3 mA. Consequently, this has been removed. The other (red) diode on the board only lights up during start-up sequence and was left on the board
- The onboard 3.3V regulator allows different voltages to be connected to the board through the BAT+ connection (4.5-16V). However, the regulator is a substantial energy consumer and with two AA alkaline batteries in series (providing 3-3.2V), the board is powered directly without the regulator

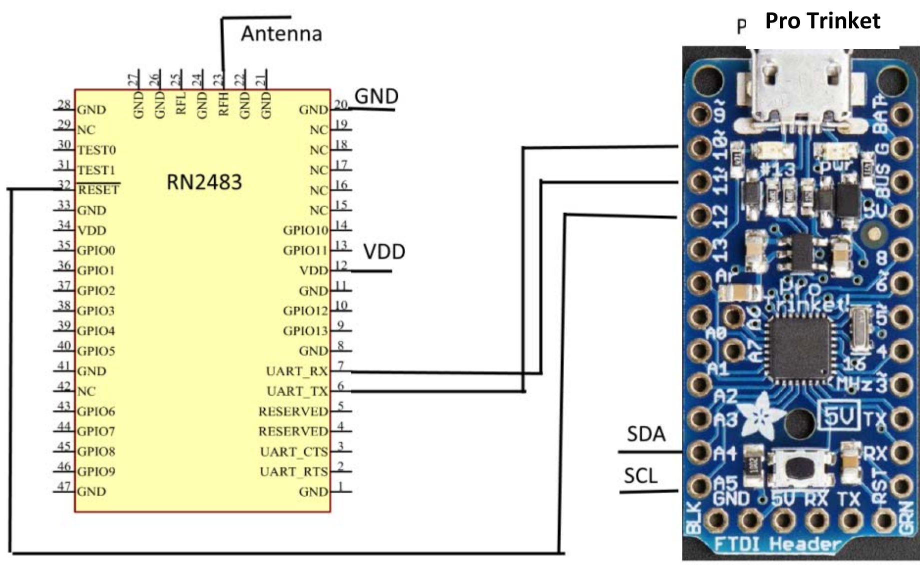

Figure 3: Wiring diagram between Pro Trinket and RN2483

2.3 Node software

The software for the nodes is made with the Arduino Integrated Development Environment (IDE), which can be downloaded form arduino.cc. This project uses the currently newest version 1.8.5

Table 1: Required Arduino libraries for the nodes

Library	Version used
SoftwareSerial	1.0.0
TheThingsNetwork	2.5.7
CayenneLPP	1.0.0
OneWire	2.3.4
DallasTemperature	3.8.0
Low-Power	1.6.0
HIH61xx	2.0.1
AsyncDelay	1.0.2

The software is made to be versatile. Each sensor type has an ID-number, and to add new sensor types, this should just be added in the software. During start-up, the node searches for the diffferent sensor types and if found, the read value is included in the data transmission packet.

2.4 Sensors

In general there are two types of sensors, analog and digital. This platform uses digital sensors as they are straight forward to implement, as long as they can operate at the voltage of the system, and connect to the microcontroller with I2C, SPI, Two Wire, one Wire or similar protocols. Also, they come pre-calibrated from the production. Also, digital sensors emit less heat, which reduces the negative impact on other temperature-sensitive sensors.
The platform was tested with the high-end combined air temperature and humidity sensor HIH6120 from Honeywell and a couple of OEM water-proof DB18b20+ sensors with extension cords.

2.5 Battery life

The current draw was measured during sleep, wake-up, measuring, transmitting and receiving as illustrated in Figure 4. Table 2 lists the exact values. The sensor node is set-up to transmit and to listen twice for acknowledgements from the gateway, 1 and 2 seconds after the transmission.
The node runs on 3.0 V battery pack provided by either rechargeable or alkaline batteries of type AA. Alkaline batteris of this size typically comes with the capacity of 1500 mAh, and Table 3 lists the expected battery life

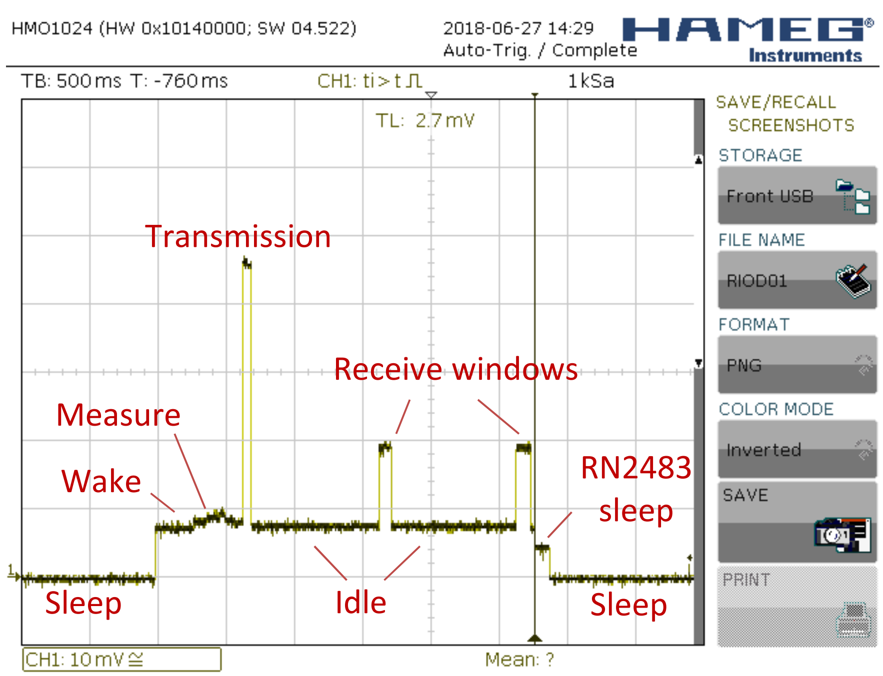

Figure 4: Current draw during different node states

Table 2: Current usage in the different states with a payload of 17 bytes

Library	Time	Current
Transmit	73 ms	46 mA
Receive	200 ms	19 mA
Idle	2450 ms	7.3 mA
Sleep	-	4 μA

Table 3: Battery life estimate on two AA 1500 mAh alkaline batteries

Sample rate	1min	10 min
Awake average	9.2 mA	9.2 mA
Total average	421 μA	45 μA
Battery life	148 days	1367 days

2.6 The Things Network

There are many suppliers of LoRaWAN's but one popular one is the free service from The Things Network (TTN). The network is community driven, meaning that all members can setup their own gateway, and give the whole network access to it through TTN. TTN then supply the backend infrastructure.

Because TTN is community driven a fair access policy is implemented which limits how much each device can uplink and downlink. Each device can uplink a total of 30 seconds each day, and receive a total of 10 downlink messages a day. The limitation of 30 seconds will limit how often as well as how many times a device can uplink messages each day. The air time depends on how large the payload is, as well as the spreading factor (SF). The limit on downlink messages is due to the fact that while the gateway can receive on 8 channels at a time, it can only transmit on one channel.

The only downside of using The Things Network as 'relay station' is the downtime which is higher than for competing and commercial platform Loriot.io. Also the Fair Access Policy has too downsides:

- if you need coverage in places far from the gateway, and thus need higher spreading factors, or just need a short interval between transmissions
- confirmation that every message sent is also received by the network server is not possible

2.7 Range

The range was tested with a spreading factor of 7 and a bandwidth of 125 kHz, which has the shortest range, but highest data rate. The range was tested at DTU by testing the throughput of data from various distances between node and gateway, as illustrated on Figure 5. The red dot is the gateway. At position A approx. 50 m from gateway all messages are received, at position B, not all, at position C, none. There are approx. 8 concrete walls between the red dot and position A.

Figure 5: Range test in built environment. The gateway is located in the red dot.

3 DATA MANAGEMENT

The Things Network merely acts as a transmission agent and therefore a server, or in this low-cost focused case, aRaspberry Pi, must be ready to receive the data. The Raspberry Pi runs Debian OS and has 16 GB of SD-card storage, enough to store data from hundreds of nodes for many years. On top of the Debian OS, the Raspberry Pi runs Node-RED, influxDB and Grafana for data management.

3.1 Node-RED and influxDB

Node-RED is a programming tool for wiring together hardware devices, APIs and online services. It provides a browser-based editor that makes it easy to wire together flows using the wide range of nodes in the palette. In this implementation, Node-RED has been used to wire the incoming data from The Things Network with influxDB, which is an open source database specialized in time-series data.

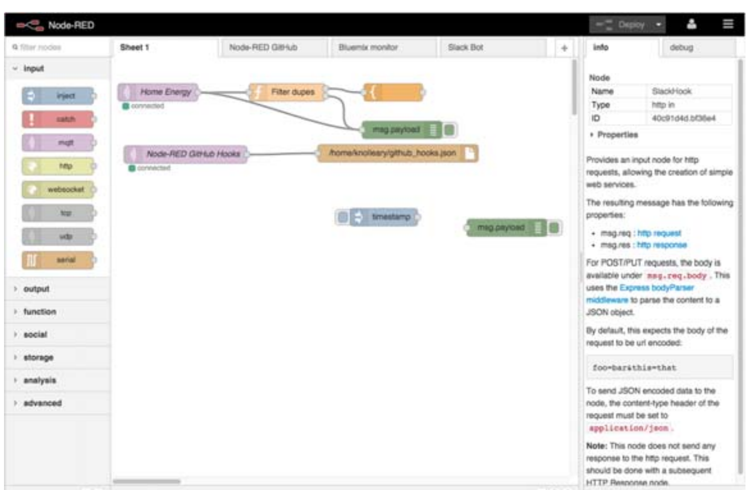

Figure 6: Illustration of the browser-based ‘wiring’ tool that combines incoming transmission data with the influx database.

3.2 Visualization

For visualizing the data and providing metrics, we find the open-source analytics platform Grafana to be suitable (Grafana, 2018). Grafana allows you to query and visualize your data in customizable dashboards like the one shown in Figure 7. Note that the battery voltage may also be part of the data packet. In this manner, the battery power may be supervised and alerts be created.

Figure 7: Example of Grafana customizable dashboard.

4 COSTS BREAKDOWN

The cost-benefit ratio is essential when deploying a large number of extra sensors in buildings. Consequently, the initial costs as well as the running costs of the sensor network, the data storage and the processing are listed in Table 2. The hardware has some initial costs, as well as the batteries

Table 4: Cost breakdown of sensor network

Component	Approx. price ex VAT (Euro)
Arduino	10
Radio chip	13
Antenna	7
Battery container	1
Temp + RH sensor	10
Node container	5
Sum Per Node	46
Raspberry Pi	35
SD-card 16 GB	14
RP container	6
Gateway (TTN)	300
Software	Open source

5 IMPROVEMENTS

There are a number of improvements that present6s themselves:

- The Arduino micro-controller and the RN2483 radio module can be fused together on a printet circuit board which saves some minor components and creates multiple loss-free connections between MCU and radio chip.
- The range can be improved if the wire from the RN2483 radio chip to the antenna is matched with the characteristic impedance of 50 Ω. The solution to this matching problem is a printet circuit board made for the module and antenna, this way it is much easier to control the impedance, through the dimensions of the trace going from the module to the antenna. Without the correct matched connection, some of the energy delivered from the transmitter to the antenna, is reflected, which means that the signal is not as strong as it could be.
- To use energy harvesting, the alkaline batteries may be replaced with a LiPo rechargeable battery in combination with a PV-element or a Peltier-element, but at the expense of introducing a power consuming voltage regulator. Hence, the energy harvesting solution is a trade-off between battery life on ordinary non-toxic alcaline batteries, the energy available for harvest and the parasitic energy losses related to storage and voltage regulation.
- There is a commercial alternative available to the sensor nodes: The Things Uno board made by the The Things Network. The Things Uno is a prototyping board in the Arduino uno formfactor, which provides the microcontroller and the LoRaWAN compliant RN2483 module made by Microchip. Both the node and the uno, can be programmed with the Arduino IDE, to fit the needs of the user. The price for The Things Uno is 50 euros excluding accessories.

6 CONCLUSIONS

The paper presents a readily available platform that can help facility managers and researchers alike to gain insight into building operation using a generic low-cost hardware and software platform. The Arduino platform provides a versatile platform for development of the node software, and plenty of libraries for the hardware. The node software, provides a versatile approach to sensors, and automatically detect when a sensor is connected, and sends the data to the gateway without customisation.

In terms of battery life, the platform can operate for years on ordinary alkaline batteries and in terms of range, the hardware seems also to perform adequately with the LoRa radio transmission protocol, but can be improved with better antenna design.

The Grafana, InfluxDB and Node-RED combo is a powerful solution for visualisation of the data, and is available for free.

7 ACKNOWLEDGEMENTS

We would like to express gratitude towards Martin Nordal Petersen at DTU Photonic who gratefully provided us with the loan of a LoRaWAN compliant gateway.

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