A Demonstration of Low Power Wide Area Networking for City-Scale Monitoring Applications

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Abstract. Networks of sensors are key components of an Internet of Things. This paper outlines a demonstration of a wireless technology called LoRa/LoRaWAN that may be used to network sensors over a range of several kilometers. LoRa is an example of a Low Power Wide Area Network (LPWAN) and features hardware, software and network protocols especially designed to achieve wide area coverage with exceptionally low power consumption. However, these features constrain effective data rate and multiplexing capabilities. Our demonstration applies LoRa to an Environment Monitoring and Electrical Power System application where these tradeoffs are justified.

Keywords: IoT · Internet of Things · LPWAN · Environment monitoring · LoRa · LoRaWAN · Sensor network

1 Introduction

Internet of Things (IoT) is a broad concept that addresses the advantages and concerns of connected 'Things' such as computers, devices, sensors, etc. These Things can be diverse in terms of function and core technology, necessitating an equally diverse set of connectivity solutions differing in range, data rate, and energy consumption. In the case of wireless connectivity solutions, fundamental limits prevent a single wireless networking panacea to cover all possible connectivity application requirements. Consequently, expansion of IoT applications has created opportunities for innovation in wireless technologies to address application specific tradeoffs. LPWANs (Low Power Wide Area Networks) are class of networking technologies that aim to minimize energy consumption while retaining wide area coverage. Typical LPWAN applications include sensors which must operate for years with an operational range of several kilometers, but with batteries that cannot be easily replaced.

The tradeoffs addressed by LPWANs are not new: For example, NASA's Voyager 1 and Voyager 2 spacecraft launched in 1977, are still transmitting to earth from beyond our solar system despite being constrained by the limited onboard energy

M. R. Palattella et al. (Eds.): ADHOC-NOW 2019, LNCS 11803, pp. 608–618, 2019.
https://doi.org/10.1007/978-3-030-31831-4_44

supply. The LPWAN options discussed in this paper and the example application presented are low cost, terrestrial use cases in which the hardware involved is barely larger than a postage stamp.

2 LPWAN Solutions

Numerous LPWAN solutions exist, in various stages of maturity. The Internet Engineering Task Force (IETF) published a Request for Comments (RFC) 8376 [1] describing four LPWAN options: LoRaWAN, NB-IoT, Sigfox and Wi-SUN. It is unclear why the IETF selected a subset of those four LPWAN options for RFC-8376. We decided to evaluate a larger set of LPWAN solutions prior to developing our demonstration, including:

- LTE-M
- NB-IoT
- Sigfox
- Wi-SUN (FAN, RLMM, JUTA, ECHONET)
- IngeNU (formerly On-Ramp Wireless)
- Weightless (N, P, and W)
- DASH7
- LoRa/LoRaWAN
- LoRa/M.O.S.T.
- LoRa/Symphony Link

2.1 Selection of a Representative Technology for Demonstration

For this demonstration, it was decided to use a technology with the following properties:

1. It provided visibility into the network stack (i.e., was not a proprietary and closed end-to-end solution).
2. It included security protocol specifications.
3. It integrated all the components needed for a sensor network application.
4. It did not require access to the public internet for operation.
5. It had a mature design with established evidence of end-user adoption.

Many of the options we evaluated did not fully meet these criteria and were not considered for this demonstration. The technology we selected for our demonstration is LoRa/LoRaWAN. LoRa is a proprietary wireless technology, but LoRaWAN is an open communication standard. It does not require the public internet for operation and it can be deployed entirely using private infrastructure. LoRaWAN also has security specifications included and appears to be widely adopted [2].

The LPWAN demonstration described in this paper uses LoRa/LoRaWAN for an environment monitoring use case in the electrical power system.

3 LoRa/LoRaWAN Overview

Figure 1 provides a simplified overview of the LoRa/LoRaWAN topology. Note that a full implementation requires four major components: the End-Nodes (such as sensors) to be wirelessly networked; a Gateway that communicates wirelessly with the End-Nodes; a Network Server to handle low level logical networking functions such as producing and verifying network session keys; and lastly an Application Server to handle user-controlled higher level data pipeline functions such as application session keys and data schemas.

In a real deployment, there may be more than one Gateway. Multiple Application Server instances may also exist to handle different End-Node data schemas/types. Figure 1 adequately represents the core operating principles of the majority of competing solutions to LoRa/LoRaWAN. Note that LoRa is a specification for the sub-GHz radio frequency link between a Gateway and End-Nodes while LoRaWAN is a specification for the data pipeline between the End-Nodes and the Application Server. This distinction is outlined in the following two sub-sections.

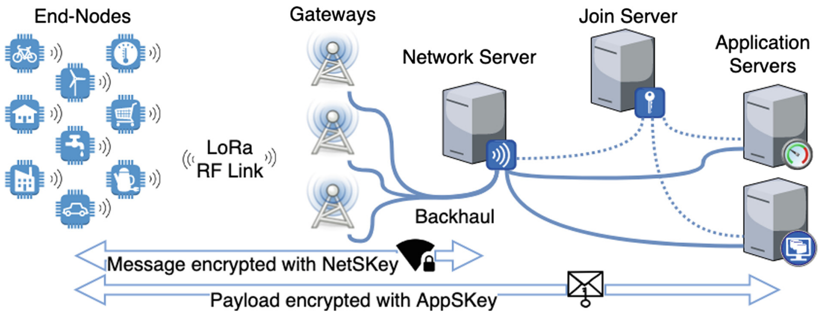

Fig. 1. LoRa/LoRaWAN topology

LoRa. Although sometimes used interchangeably, LoRa and LoRaWAN refer to different concepts. LoRa (Long Range) is a chirp spread spectrum (CSS) modulation technique [3]. LoRa Modulation operates in sub-GHz license free ISM bands [4] with variable Spreading Factor (SF). Radio modules vary SF automatically to optimize between data rate and range while keeping radiated power constant. Depending on the SF and bandwidth in use, bit rate varies between 250 bps and 21.9 Kbps. At longer range, the effective data rate is reduced resulting in longer transmit times and the proportional increase in total energy needed per bit.

Most ISM bands are duty-cycle restricted resulting in a limit on payload size at a given SF. Maximum duty-cycle is 1% in Europe, thus each frame may be between 51 and 222 bytes. In the United States, restrictions on the dwell time to under 400 ms [4] effectively limit the maximum payload to between 11 bytes and 242 bytes.

Range is estimated to be about 2 km in urban areas, and 10 km in suburban areas with unobstructed line-of-sight [5].

LoRaWAN. This is the specifications for the (Media Access Control) MAC protocol [6]. The specification is open and maintained by the LoRa-Alliance [7] comprised of industry, academia and research institutions. The logical network has a star-of-stars topology with an addressing scheme that is not Internet Protocol compatible due to optimizations applied with the aim of reducing transmission time. LoRaWAN features end-to-end encryption with two keys: the Network Session Key which encrypts LoRa frames to secure addressing and routing information and the Application Session Key which encrypts payloads, this key is owned by the application developer/user.

Advanced power optimization is achieved by integrating End-Node sleep and transmitter synchronization functions within the specification. To save power, an End-Node enters a power saving 'sleep' state and 'wakes' to transmit a message. During sleep, the End-Node is unable to receive messages from Gateways- increasing latency. Three modes of operation balance energy consumption with reception latency by regulating when an End-Node opens a reception window: always receiving thus never sleeping (called Class C); receiving after each transmission and sleeping for the rest of the time, (called Class A); and periodically opening reception windows (called Class B).

Just like Wi-Fi—where the end-user is able to buy Wi-Fi adapters, access points; and deploy, use, and manage a wireless local area network—LoRa/LoRaWAN allows the end-user to own, deploy, and manage the hardware for a wireless wide area network. It is unique in that it lets the end user the freedom to control both the wireless infrastructure as well as the data pipeline. For those users who prefer not to deal with network deployment, there are several network service providers offering LoRaWAN based IoT solutions. Cellular telecommunications companies are rolling out nation-wide coverage [8] and there are community network operators offering non-comprehensive global coverage [9].

4 LPWAN Demo

For this demonstration, an entire LoRaWAN based infrastructure is deployed on premises with the aim to demonstrate an application of LPWANs in monitoring the environment across a city. This demonstration shows how both static sensors and mobile sensors may be integrated to build a sensor network that can be used to optimize the dispatch of distributed photovoltaic generators.

4.1 LPWAN Demo Architecture

The LPWAN Demo Architecture is illustrated in Fig. 2. One static End-Node consisting of a set of environmental sensors is placed within Gateway coverage range, with data reported from the End-Node over the LoRaWAN infrastructure to a web-based dashboard. The LPWAN infrastructure is shared with another parallel data pipeline from a mobile End-Node reporting its Global Navigation Satellite System (GNSS) coordinates periodically. These coordinates are displayed on a continuously updated map showing the mobile End-Node's last location.

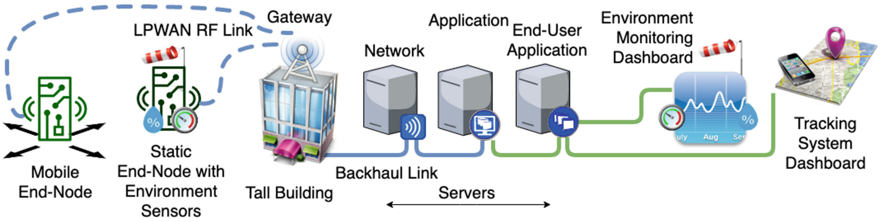

Fig. 2. LPWAN Demo Architecture based on LoRa/LoRaWAN showing both static and mobile End-Nodes and their respective dashboards.

End-Nodes. Both static and mobile End-Nodes are based on the same prototyping platform called a Pycom FiPy Development module. It has an Espressif ESP32 SoC, five network interfaces: Bluetooth, Wi-Fi, LTE-M, Sigfox, and LoRa. FiPy development module has a Micro-Python interpreter to execute software.

For the mobile End-Node a Pycom PyTrack is added to the prototyping platform. The PyTrack board includes a 3-axis accelerometer and a GNSS receiver to compute location, shown in Fig. 3-left.

For the static End-Node, a Pycom PySense expansion board is added that provides environmental measurements like Temperature, Humidity, Barometric Pressure, Ambient Light, and 3-axis accelerations. Specifications for the Pycom products used are available on the Pycom website [10].

Each End-Node is adequately powered by a 5 VDC, 0.5 A power supply and is connected to a 4 dBi whip antenna.

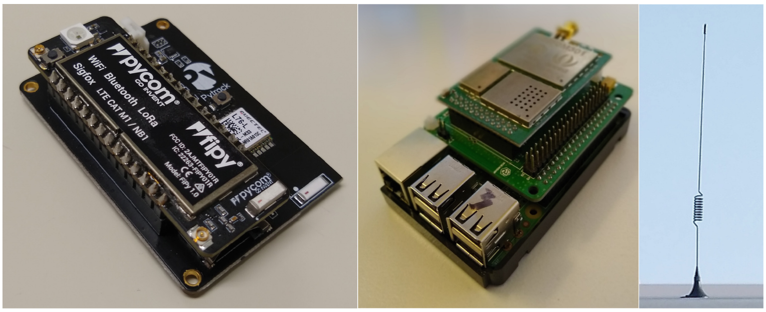

Fig. 3. Equipment used in Demo. Left: Pycom FiPy Development Module mounted on PyTrack (as Mobile End-Node). Center: Gateway module RisingHF RHF0M301 mounted on Raspberry Pi. Right: 4 dBi Antenna. Images are not to scale.

Gateway. The LoRaWAN Gateway is an interface between LoRa and an Internet Protocol Switching Network. The Gateway maintains two independent network interfaces, a LoRa interface to communicate wirelessly with End-Nodes and an independent Ethernet interface to maintain a backhaul connection with the Network Server.

The backhaul connection may be alternatively served by a cellular data link or WLAN link.

The LoRa interface on a Gateway has more functionality than the interface on End-Nodes. Each Gateway has two LoRa transceivers. Together they cover eight 125 kHz bandwidth channels and one overlapped 500 kHz LoRa Channel. Behind these two transceivers there is a digital signal processor (DSP) that demodulates received signals. Each 8 + 1 channel set is called a sub-band. There are 8 sub-bands in the US-915 spectrum allocation. Gateway implementations vary on how many sub-bands are utilized. Digital multiplexing between channels enables Gateways to maintain simultaneous connections across all channels in all available sub-bands.

A packet forwarding program is used to maintain an uplink where all valid LoRA frames are forwarded to the Network service. The program also maintains the downlink sending packets from the Network Server to the appropriate Gateway for transmission.

For this demonstration, a packet forwarder made by Semtech is used. The forwarder runs on Raspbian OS on a Raspberry Pi 3 single board computer. The Gateway used is comprised of a RisingHF RHF0M301 [11] LoRA interface mounted on a Raspberry Pi 3, shown in Fig. 3-center. This gateway module covers 8 + 1 channels in a sub-band. The Gateway uses a weather proof 4dBi antenna with a magnetic base (see Fig. 3-right). The same kind of antenna is used for the End-Nodes as well.

Network Server. The Network Server manages the LoRaWAN network by registering Gateways and End-Nodes. The Network Server receives LoRa frames wrapped in IP packets from the Gateway. If the same LoRa frame is received by more than one Gateway, the Network Server discards duplicate frames. The Network Server also decrypts messages using the Network Session Key while retaining the encrypted message payload. Finally, the Network Server routes encrypted payloads to the respective Application Server based on header information.

For outbound messages (downlink), the Network Server receives encrypted payloads from Application Servers and doubly-encrypts the message using the Network Session Key. Then, the network server assigns the transmission of the LoRa frame to the Gateway that received the most recent uplink with the strongest signal.

When End-Nodes allow it, the Network Server also regulates the data rate for the network by sending MAC-commands to End-Nodes to adapt their modulation increasing the spreading factor – a mechanism called Adaptive Data Rate (ADR).

There are a plenty of options for Network Servers. For this demonstration, a free opensource Network Server called LoraServer [12] is used.

Application Server. From the perspective of the LoRa/LoRaWAN topology, the Application Server is the terminal end for LoRaWAN traffic. This server owns the Application Key and is able to encrypt/decrypt message payloads, protecting it from the rest of the LoRaWAN infrastructure. Once decrypted, payload has to be decoded to obtain sensor data. Message coding is out of scope of LoRaWAN specification. It is up to System Infrastructure Designer to decide whether to use a custom coding, or to adopt a de-facto standard like the CayenneLPP codec [13]. Sensor data may be passed to a diverse set of user applications through System Integrations, according to system functional specifications.

For this demonstration, the Application Server module (part of LoRaServer implementation) decodes payloads (using CayenneLPP codec) and transfers sensor data through an InfluxDB integration.

End-User Application Server. Beyond the LoRaWAN Specification, but present in any LPWAN implementation, there is at least an End-User Application. This could be a software application, or combination of several software applications working collaboratively on one or more computers according to system functional specifications.

For this demonstration, sensor data received from Application Server is persisted in an InfluxDB [14] database. Stored sensor data is represented using a dashboard visualization tool called Grafana [15].

4.2 Demo Deployment

This demonstration uses all the components described above to build an integrated LoRaWAN solution to collect and display sensor data.

Static End-Nodes are placed at a meaningful distance from the Gateway. Mobile End-Nodes are attached to a vehicle of some sort that demonstrates the robustness of the protocol to a quickly changing RF environment. Both types of End-Nodes are battery powered.

The Gateway antenna is located to maximize radio signal quality, which ideally means locating the Gateway antenna on a tower, building rooftop or balcony with unobstructed sight lines to all of the End Nodes. The Gateway is connected to a power source and a network connection for backhaul (Ethernet is preferable). Our antenna is a 30 cm tall weatherproof whip with a magnetic base. The same antenna is used for both the Gateway and the End-Nodes.

A computer running instances of Network, Application, and End-User Servers is connected to the Gateway. A display connected to this computer presents sensor dashboards and relevant information pages.

5 A Power Systems Use Case for LPWAN Based Sensor Network

Although at first sight it may seem that wireless sensor networks used to monitor the electrical power system are rarely energy constrained, wireless sensors are in fact ubiquitous throughout the power system, with networks ranging from high speed WLANs used within distribution substations to satellite based wide-area monitoring platforms. Over the last thirty years, significant advances in monitoring and control practices used for power systems have resulted in several mature sensor network technologies optimized for the traditional power system.

The power system, though, is rapidly evolving to adapt to decentralized power generation and greater consumer interaction with energy markets. This demonstration is intended to highlight two specific use cases where an LPWAN may be used in the power system of the future.

5.1 Local Demand Models

The first use case considers the trend towards more local/ decentralized models for load behavior allowing an electrical distribution system to better dispatch decentralized generation.

It is known that air temperature and humidity directly affect energy demand [16, 17]. Existing methods to derive these correlations aggregate vast amounts of data from diverse climates and load portfolios to build ensemble forecasts. It is anticipated that distribution system operators of the future may want to update 'weather vs. load' forecasts for cities and/or feeders based on local environmental conditions. These local forecasts will have to meet the same statistical standards as existing forecasts while using local measurements that may be prone to increased variability over shorter time scales. An important step in ensuring the statistical confidence in forecasts is the 'selection' and 'combination' of measurement time series. As discussed in [17], correlation models typically use a single virtual time series of environmental data to generate forecasts. This virtual time series is generated by optimally selecting certain measurement sites and combining them to maximize forecast robustness.

For the example of a local forecast, this process would require a sufficiently large set of measurement sites so that the forecast algorithm could initialize several populations of physical measurement series with randomly assigned weights. Individual measurements drawn across populations represent a spectrum that may be scored for bias against the validation measurement. At this point, only populations with low bias are combined to produce a forecast. Subsequent iterations update the weights to improve the goodness of fit. If this approach were to be used to forecast the load changes for a single neighborhood or city, a sufficiently large set of weather stations near the validation site would be required. Ideally, the spatial distribution of these weather stations will have to be updated several times to maximize populations meeting the selection criteria. These stations would have to operate in the field long enough to compute robust forecast weights.

These constraints justify the use of an LPWAN to collect local weather measurements. A LoRaWAN system comprised of several battery-operated weather stations would enable easy reconfiguration of measurement sites within a range of several kilometers while maximizing battery life. The entire system could be rapidly deployed; not being dependent on any other networking infrastructure. The static End-Node used for this demonstration is intended to illustrate such a battery powered weather station with environmental sensors like Temperature, Humidity, Barometric Pressure, and Irradiance.

5.2 Intra-hour Forecasts of Solar Power Production

The second power systems use case is premised on recent developments in the real-time optimization of distribution grids. Real-time optimization presents several computational and implementation challenges. One of the frequently cited implementation challenges is the tight coupling between convexity of the optimization problem and the determinism in real-time updates to the system state. Traditional power systems treat variations in measurement timing as independently distributed sensor noise, but as optimization time scales are reduced and decentralized algorithms are used to solve optimization problems, temporal variations are known to induce instabilities in the solution.

A specific case where temporal determinism is required of measurements obtained over a 50 km $\times$ 50 km area is in forecasting the short time scale output of photovoltaic systems in urban environments. Consider the methodology proposed in [18] where a sensor network is proposed to monitor changes in surface irradiance over a 2500 km^2 area. The sensor grid is comprised of sensors placed approximately 3 km apart reporting irradiance measurements every 15 min. The authors also propose an approach to optimize sensor placement in order to improve the quality of the forecast. This optimized sensor placement may not coincide with existing network communication infrastructure but can be shown to minimize the root mean square error of the forecasts. The need for determinism is highlighted in the observation that velocimetry-based forecasting methods are inherently dependent on the spatio-temporal correlation of irradiance ramp-rates (caused by clouds moving relative to the sun) in a given geographical area. Most existing algorithms estimate velocity by analyzing the pairwise covariance in ramp-rates for irradiance sensors. Forecast errors are directly affected by uncertainty in the covariance computed for all possible pairwise combinations of sensors in the network.

One can see how this use case would be well served by an LPWAN. First, the operational area required is within the specification for LoRa. Second, the poll rate of 15 min for a sensor network of a few hundred sensors is within the bandwidth limits for LoRaWAN. Third, the low-power/ portable nature of sensor End-Nodes allows them to be placed conveniently and therefore more closely reflecting the ideal placement for minimum error. Lastly, the need for determinism in the data collection process is critical to accurate velocimetry. By adopting a LoRaWAN system, the end user is not subject to the varying network latencies of a cellular connection. Also, the system designers have ownership of software in the Gateway and Network Server allowing direct control over the logical scheduling used to obtain each sensor measurement. This control allows much more precise time alignment of measurements and also allows the network schedule to be updated to match the pairwise correlations being computed by the forecasting algorithm further improving the forecast accuracy.

For our demonstration, we use a battery powered mobile End-Node that transmits location periodically while affixed to a moving vehicle, as a proxy for this application. The mobile End-Node has to meet all the performance requirements described in the previous section while also reporting measurements in a deterministic fashion in order to accurately report the real-time position of the vehicle being tracked. Variations in the reporting rate are clearly illustrated as gaps in the tracks presented in the visualization.

6 Discussion

This paper presents a demonstration of Low Power Wide Area Networking for city-scale monitoring applications illustrated using a power systems use case. However, this is only one of many use case scenarios with requirements such as a broad coverage area, massive deployment of inexpensive sensors, or restricted power consumption that could take advantage of LPWAN features. LPWAN extends IoT beyond the capabilities provided by regular telecommunications technologies such as Wi-Fi, Bluetooth, V-Sat, 4G, etc. The use of LPWAN in traditional disciplines such as Agriculture [19], Wildlife protection [20, 21], and Environmental Monitoring [22]—among others—makes it possible to obtain more and better information for decision making.

Disclaimer

Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

Acknowledgement. Many thanks to Monsieur Erwan Rohou, for his generous willingness to provide LuxTram vehicles to make this demonstration possible. Special thanks to all the colleagues of the NIST Smart Grid Program for invaluable collaboration to make this happen. Many thanks to Dr. Raghu Kacker and Gustavo Escudero, for their infinite trust and support. Many Thanks to Héctor Laiz and Osvaldo H. Jalon, for trusting my professionalism to represent INTI with world-class excellence abroad. Infinite thanks to Maria Betania Antico, for incommensurable help, support, and patience to empower my professional career.

References

1. Farrell, S.: Low-Power Wide Area Network (LPWAN) Overview. IEEE (2018). https://buildbot.tools.ietf.org/html/rfc8376
2. Blenn, N., Kuipers, F.: LoRaWAN in the Wild: Measurements from the Things Network (2017)
3. Semtech Corporate: What is LoRa. LoRa-Alliance. https://www.semtech.com/lora/what-is-lora
4. LoRa Alliance Technical Committee Regional Parameters Workgroup: LoRaWANTM 1.1 Regional Parameters, January 2018. https://lora-alliance.org/sites/default/files/2018-04/lorawantm_regional_parameters_v1.1rb_-_final.pdf
5. Adelantado, F., et al.: Understanding the limits of LoRaWAN. IEEE Commun. Mag. **55**(9), 34–40 (2017)
6. LoRa Alliance Technical Committee: LoRaWANTM 1.1 Specification, October 2017. https://lora-alliance.org/sites/default/files/2018-04/lorawantm_specification_-v1.1.pdf
7. LoRa Alliance: About LoRa Alliance. LoRa Alliance. https://lora-alliance.org/about-lora-alliance
8. LoRa Alliance: LoRa Alliance Passes 100 LoRaWAN Network Operator Milestone with Coverage in 100 Countries. LoRa Alliance. https://lora-alliance.org/in-the-news/lora-alliance-passes-100-lorawantm-network-operator-milestone-coverage-100-countries
9. The Things Network: The Things Network Coverage Map. The Things Network. https://www.thethingsnetwork.org/map
10. Pycom.: Pycom Products documentation. Pycom. https://docs.pycom.io/products/
11. RisingHF: RisingHF RHF0M301 description. RisingHF. http://www.risinghf.com/#/product-details?product_id=6&lang=en
12. Brocaar, O.: About LoRaServer. LoRaServer. www.loraserver.io

13. myDevices: Cayenne Docs. myDevices.com. https://mydevices.com/cayenne/docs/lora/#lora-cayenne-low-power-payload
14. InfluxData Inc.: InfluxDB. Influx Data. https://www.influxdata.com
15. Grafana Labs: Grafana. Grafana. https://grafana.com
16. Guan, H., et al.: Incorporating residual temperature and specific humidity in predicting weather-dependent warm-season electricity consumption. Environ. Res. Lett. **12**(2), 024021 (2017)
17. Sobhani, M., et al.: Combining weather stations for electric load forecasting. Energies **12**(8), 1510 (2019)
18. Lonij, V.P.A., et al.: Intra-hour forecasts of solar power production using measurements from a network of irradiance sensors. Sol. Energy **97**, 58–66 (2013)
19. Talavera, J.M., et al.: Review of IoT applications in agro-industrial and environmental fields. Comput. Electron. Agric. **142**, 283–297 (2017)
20. Smart Parks: Smart Parks Work. Smart Parks. https://www.smartparks.org/work/
21. Semtech Corporate: Press Releases. Semtech (2017). https://www.semtech.com/company/press/Semtech-LoRa-Technology-Tracks-Location-of-Endangered-Black-Rhinos-in-Africa
22. Tzortzakis, K., Papafotis, K., Sotiriadis, P.P.: Wireless self powered environmental monitoring system for smart cities based on LoRa. In: 2017 Panhellenic Conference on Electronics and Telecommunications (PACET). IEEE (2017)