INTERNET OF THINGS AND LoRaWAN-ENABLED FUTURE SMART FARMING

Bruno Citoni, Francesco Fioranelli, Muhammad A. Imran, and Qammer H. Abbasi

ABSTRACT

It is estimated that to keep pace with the predicted population growth over the next decades, agricultural processes involving food production will have to increase their output up to 70 percent by 2050. "Precision" or "smart" agriculture is one way to make sure that these goals for future food supply, stability, and sustainability can be met. Applications such as smart irrigation systems can utilize water more efficiently, optimizing electricity consumption and costs of labor; sensors on plants and soil can optimize the delivery of nutrients and increase yields. To make all this smart farming technology viable, it is important for it to be low-cost and farmer-friendly. Fundamental to this IoT revolution is thus the adoption of low-cost, long-range communication technologies that can easily deal with a large number of connected sensing devices without consuming excessive power. In this article, a review and analysis of currently available long-range wide area network (LoRaWAN)-enabled IoT application for smart agriculture is presented. LoRaWAN limitations and bottlenecks are discussed with particular focus on their effects on agri-tech applications. A brief description of a testbed in development is also given, alongside a review of the future research challenges that this will help to tackle.

INTRODUCTION

World population is expected to grow by 2.3 billion, rising to over 9 billion people before 2050. Most of this growth is expected to happen in developing countries. As a result, the U.N. Food and Agriculture Organization predicts that food production in these countries will need to almost double. Limited and reducing amount of arable land, global climate change, growing scarcity of water, fossil fuel scarcity, and energy price are all factors that will negatively affect the food production process. In this vicious cycle, overpopulation leads to increased demand for agricultural products while also reducing the amount of agricultural destined land, converted into space for infrastructure and housing. Increasing production alone is not enough to achieve food security, and as such we need to look at solutions outside the traditional agriculture methods, creating smarter and technology-enabled agricultural solutions.

The Internet of Things (IoT) is a technological advancement capable of improving efficiency in the global agricultural landscape, accelerating progress toward the goal of increased production. By IoT we mean an architectural framework for systems where computing devices including sensors and actuators wirelessly exchange data collected from everyday objects to either a final user or other machines, in order to monitor and automate processes. It is estimated by market analysts that by 2020 a total of 28 billion devices will be connected to the Internet. This network of Internet connected objects collects relevant data with sensors to be transferred and processed remotely and gives feedback on the current status and actions needed to improve performance. Looking at agricultural applications, these sensors usually gather information about soil and weather condition, animal welfare, crop behavior, and machine status. Smart irrigation systems can, for instance, utilize water more efficiently, only watering the right amount, only in the patch of field which requires it, and at the best time. In turn, this optimizes resource consumption such as water and energy, as well as cost of labor. Such technological advances will play a fundamental role in achieving the prospected increased production requirements when coupled with artificial intelligence (AI)-based programming designed to predict potential issues and provide an adequate response. However, outstanding research issues remain such as developing sensors, communication protocols, and data processing algorithms that can satisfy all the requirements in the context of future smart farming while at the same time being sustainable and cost-effective.

Digital Object Identifier: 10.1109/IOTM.0001.1900043

This article is structured as follows. An introduction to low-power wide area networks (LP-WANs) is presented in the next section. Then a review of long-range (LoRa) and Lo-RaWAN is presented, followed by a discussion of current state-of-the-art applications for smart agriculture. We then discuss LoRaWAN technology bottlenecks. Future directions in research are discussed, followed by concluding statements in the final section.

COMMUNICATION PROTOCOLS AND IOT

Fundamental to the IoT revolution is the adoption of a communication technology that can satisfy requirements on three fundamental metrics: energy efficiency, coverage, and scalability. Traditional short-range protocols such as Wi-Fi and Bluetooth, as well as long-range ones such as cellular and satellite communication, fail to provide the required performance to the IoT deployments in smart agriculture and other similar industrial applications. While these protocols in fact are established, neither short-range technologies nor long-range ones are suitable for deployments over a vast area, with sensor nodes that are meant to be "deployed and forgotten": capable of operating for as long as possible with little to no maintenance [1].

Cellular technologies are flawed by design, as they can handle the high data rates of multimedia traffic, allowing only relatively few devices to connect to each base station while granting them wide bandwidth. This is the opposite of what is required by IoT, where a high number of sensor nodes only need the bandwidth necessary to transmit a few bytes every few minutes. This makes long-range technologies impossible to be scaled up without increasing costs and energy consumption. Satellite coverage, while having possibly the best range of all the technologies, is simply too expensive and energy-inefficient for multiple-sensor applications [2]. Short-range communications protocols such as Wi-Fi and Bluetooth suffer partly from the same design flaw as cellular. Although these technologies are in use in some agri-tech applications today, they were also designed to handle a higher volume of data than is required for standard IoT purposes at the expense of increased power consumption, which makes them infeasible for battery-powered devices to be used in rural areas and difficult to access in agricultural and natural environments. These shortcomings were mitigated with the introduction of lower-energy protocols based on IEEE 802.15.4 and designed for wireless sensor networks such as ZigBee. However, their mesh network architecture presents challenges when increasing the amount of connected devices past a certain number without exponentially increasing the network complexity and its power

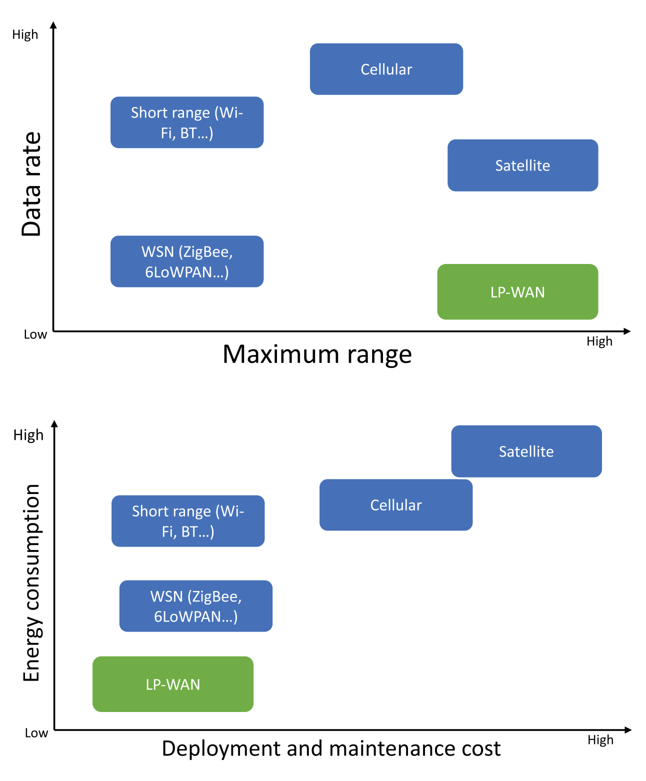

FIGURE 1. Comparison of main IoT enabling communication technologies in terms of range, data rate, energy consumption, and costs.

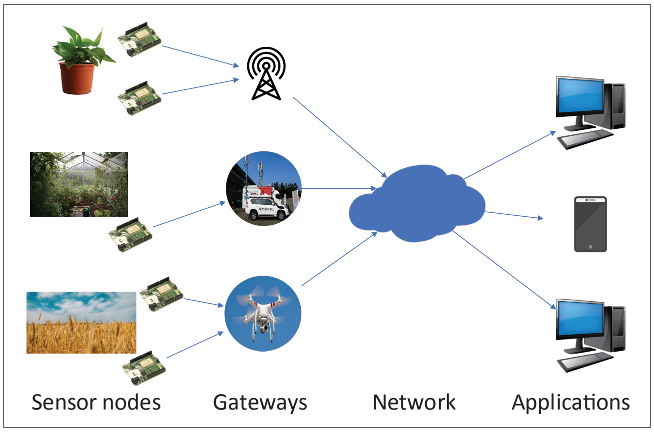

FIGURE 2. Typical star-of-stars LoRaWAN network topology.

consumption. For large-scale, sustainable applications over vast areas, both the long-range communication available to cellular and satellite, the lower deployment costs associated with Bluetooth and Wi-Fi and the power consumption of protocols designed with wireless sensor networks in mind such as ZigBee are needed.

LP-WANs are a type of wireless communication network designed to fit all these specifications. While unsuitable for heavy data transmission and multimedia streaming due to very narrow band and low data rate, they can easily support the transmission of small packets of data from sensors and to actuators, minimizing power consumption and design complexity, and thus costs. This is shown in the visual comparison of technologies according to several performance metrics in Fig. 1.

LoRa and LoRaWAN

LoRa is a derivative chirp spread spectrum (CSS) modulation technique and proprietary physical (PHY) layer developed by Cycleo to achieve high-range low-power communication. LoRaWAN is a medium access control (MAC) layer protocol built on LoRa, and its specifications are openly available as well as being endorsed by the LoRa Alliance.

LoRa Physical Layer

LoRa uses the licence-free region-dependent industrial, scientific, and medical (ISM) frequency bands: 863–870 MHz for Europe and 902–928 MHz for the United States. However, it can also be set to operate in the lower ISM bands of 433 MHz and 169 MHz.

While this makes the deployment cheaper due to the use of the unlicensed ISM frequency spectrum, it also restricts the maximum achievable data rate because of regulations on available air time per device on the same frequencies. The enforced duty cycle is 1 percent for the commonly used frequency sub-bands of 863.00–868.00 MHz and 868.00–868.60 MHz. Each sub-band must remain "silent" for a period of time that is proportional to the time on air of the packet and the maximum available duty cycle enforced [3]. For instance, for an air time of 1 s and a duty cycle of 1 percent, the sub-band will have a 99 s mandatory silence time. This restricts the available air time per device to roughly 36 s per day, which makes LoRa unsuitable for high data rate applications. LoRa devices usually can transmit over multiple channels (defined by different center frequencies) and utilize channel-hopping algorithms that aim to find the best possible channel on which to transmit the data in order to try and mitigate this drawback.

Using a lower frequency than Wi-Fi and cellular has the benefit of granting a higher penetration through walls and ultimately a high maximum range. In the range study carried out by J. Petäjäjärvi *et al*. "On the Coverage of LP-WANs: Range Evaluation and Channel Attenuation Model for LoRa Technology" (2015), this is quoted to be up to 15 km in rural open space and 2–5 km in urban environments, with increased range if there is direct line of sight between devices and gateways.

LoRa has a number of configurable parameters that give flexibility to the designer in regard to the maximum achievable communication range, power consumption, and data rate.

- Spreading factor (SF), which is related to the number of chirps that are used to encode a single bit of information in the modulation of the message. Larger spreading factors increase the signal-to-noise ratio (SNR) and therefore the communication range, at the cost of slower transmission and longer airtime for each packet. Depending on the SF in use, data rate ranges from 0.3 kb/s to 27 kb/s [3].
- Bandwidth (BW), which is the range of frequencies over which the LoRa chirp spreads. Higher bandwidths increase the data rate of packets but reduce communication range. The most common bandwidths available are 125, 250, and 500 kHz.
- Coding rate (CR), which refers to a programmable number of bits that are added to the packet header in order to perform forward error correction techniques. Larger coding rates increase resilience to interference, but also increase packet length, air time, and energy consumption [4].

LoRaWAN MAC Layer

LoRaWAN is one of the available MAC layer protocols built upon LoRa. It has recently gained a lot of attention due to its characteristics, which make it particularly suitable for IoT.

LoRaWAN networks comprise three main elements:

- Nodes: sensor boards responsible for collecting data or implementing instructions via actuators through communication with gateways
- Gateways: Internet-connected devices that forward the packets coming from the nodes to a network server acting as a logically invisible bridge between nodes and network

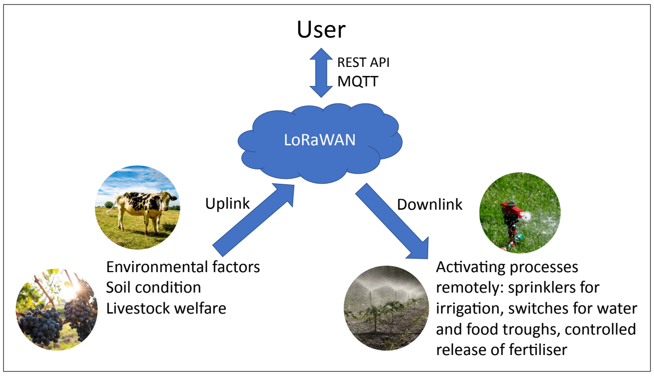

FIGURE 3. Typical downlink and uplink contents in LoRaWAN-enabled agri-tech deployments.

- The network server, which handles the de-duplication of received packets, rejection of corrupted/unwanted ones, as well as scheduling messages to be sent to specific nodes through gateways in range

A typical LoRaWAN network is organized in a star-of-stars topology where nodes do not have a direct connection to any single gateway but instead transmit to all gateways in range. Figure 2 shows an example of topology for a hypothetical smart agriculture application, where different sensing nodes can communicate with different gateways (fixed or mobile based on vehicles or drones). This is different from mesh topologies typically utilized by wireless sensor networks (WSNs), where clusters of devices communicate to sinks they have to associate with directly, and which in turn forward the message on. These multihopping topologies effectively trade off power efficiency for higher transmission range. Thanks to this limitation, the estimated lifetime of a single battery-powered LoRaWAN connected sensor device is expected to be years, which results in cheaper deployment and maintenance as well as an overall simplified network design [1], [2]. The maximum recorded range achieved by an unconfirmed uplink message using LoRaWAN is 702 km.

The gateway relays the data it receives from all the nodes in range to the network server associated with each node. Communication is bidirectional, so devices can send data to the network via uplink and receive instructions via downlink. However, the uplink direction is strongly favored. Direct communication between two nodes is not available with LoRaWAN, requiring the data to pass through a gateway in both uplink and downlink for this to be achieved. These limits preclude the use of LoRaWAN to time-critical, low-latency applications.

Other custom protocols can be built on the LoRa PHY layer. LoRaBlink was developed in [5] to achieve multihop, robust, and low-latency communication, while keeping a low energy profile. Symphony Link™ is another protocol that aims to resolve the problem of scalability outlined by different researchers by implementing a range of different features [6].

LoRaWAN: State-of-the-Art Applications for Smart Agriculture

Based on the characteristics outlined so far, LoRaWAN technology has the potential to be applied effectively to many Industrial IoT (IIoT) applications. In these scenarios only small amounts of data need to be analyzed and monitored, with the additional requirement of sending sporadic downlink messages. In an agri-tech context in particular, sensor nodes usually are interested in monitoring environmental factors such as temperature and humidity, as well as health conditions of livestock and chemical conditions of soil and plants. These are often factors that do not require up-to-date real-time monitoring, but need only an update every few minutes. This effectively works around one of the main drawbacks of the LoRaWAN technology, its limitation in maximum data rate. Downlink messages typically are used to activate simple devices such as solenoid valves and switches like a sprinkler to perform watering of a specific portion of a field or a dispenser to refill food and water troughs for livestock.

The most common IoT applications for agri-tech currently being researched and developed include:

- Automatic irrigation control: optimizing water usage in farming by monitoring soil condition and intelligently activating sprinklers
- Large and small arable farming: including soil monitoring, chemical analysis for pests and disease, machine and agricultural manned and unmanned vehicle (drones) monitoring and control
- Livestock and animal welfare: including movement monitoring to diagnose and prevent diseases such as lameness, eating and drinking habits, and beehive monitoring
- Greenhouse and indoor horticulture: monitoring environmental factors to ensure optimal atmospheric conditions are maintained throughout the year

Generally, academic papers that focus specifically on outdoor, LoRaWAN-enabled agri-tech applications are mostly resolved as proof-of-concept small-scale testbeds for future research, or investigations on the feasibility and performance of the protocol for different use cases. Table 1 includes details of some of the most recent LoRa-specific IoT deployments and some metrics where specified.

On a commercial level, a host of IoT projects have been launched in recent years, mostly in the form of crowd-funded do-it-yourself (DIY) applications ranging from smart gardening gadgets to attempts to automate lawn irrigation. They usually combine LoRaWAN (when used at all) with other technologies such as cellular and Wi-Fi, and are almost exclusively small-scale deployments. In this early stage of the technology, large-scale deployments are still manly carried out by organizations that can sustain the capital cost of setting up a network as well as providing subscription to servers and data analysis tools run by third parties.

Among the successful examples of such a large-scale LoRaWAN-enabled deployment is the case of livestock monitoring in New Mexico, as reported by Actility, which also exemplifies why LoRaWAN is to be preferred in these scenarios over other network protocols. The amount of cows to monitor (up to 7000) as well as the vast areas these desert ranches occupy (10,000 to 20,000 hectares) makes the process of gathering information about livestock well-being complicated and expensive in terms of time and resources. This is partly due to the amount of animals and area to cover, but also down to stretches of land being only accessible via horse. While historically the cattle was tracked using conventional GPS devices, the lack of consistent cellular coverage over the whole grazing area prevented effective tracking of the cattle's location. A LoRaWAN off-the-shelf solution was able to overcome these problems thanks to its long range and high coverage, while guaranteeing a battery life of 6–7 months to various devices monitoring water level, temperature and GPS position. Where cellular technology failed, LoRaWAN helped increase productivity and security while also reducing the amount of manual work required by business owners.

Moving forward, it is fundamental to try and grow the community of LoRaWAN users as this will lower the costs associated with setting the network infrastructure. As gateways and nodes do not have a 1-to-1 direct connection, a single gateway allows users in its operating range to leverage the established public or private network for their own application. Examples of the benefit this will bring to the community are the case study of Lebanon's Château Kefraya or the Devonian Gardens in Calgary, Canada. Here, thanks to existing nationwide and citywide IoT networks, sensors monitoring, among others, soil temperature and moisture, water temperature, humidity, and luminosity could be set up within a rapid timeframe and with a reduced capital investment [15, 16].

Ref.	Application	Number of nodes	Coverage	SF	BW	Operating frequency	Payload Length	Payload content	Nature of research
[7]	Drip irrigation control	Up to four actuators per node	—	10	125 kHz	433 MHz	Max. 9 B	—	Testbed
[8]	Mushroom house monitoring and control	Three per mushroom house plus actuators	—	—	—	—	—	Temperature, humidity, and CO_2	Testbed
[9]	Maize crop monitoring	27	648 m^2	—	—	868 MHz	—	Soil moisture and temperature, light intensity, humidity, ambient temperature and CO2	Costs and power consumption evaluation
[10]	Tree Farm monitoring	—	Up to 200 m	7 to 11	125, 250 kHz	915 MHz	9 B	Temperature, humidity, solar irradiance, flame sensor	Environmental performance analysis
[11]	Irrigation control	Actuators only	Up to 8 km	12	—	433 MHz	—	—	Proof of concept
[12]	Grape farm monitoring	Three sensor nodes and one actuator node	1 km radius	—	—	—	—	Air temperature, humidity, leaf wetness and soil moisture	Proof of concept
[13]	Water troughs monitoring	Five physical sensor nodes, 100 simulated nodes	0.5 to 2.7 km	—	—	915 MHz	26 B	—	Proof of concept
[14]	Horse stable monitoring	One node	70 m	7	125	868 MHz	2 B	Temperature and humidity	Use case analyses
[14]	Agricultural land monitoring	One sensor buried 10 to 60 cm in soil	40 to 350 m	7 to 10	125	868 MHz	—	Conductivity and soil temperature	Use case analyses

TABLE 1. LoRa-enabled agri-tech applications in the literature.

LoRaWAN: Limits and Outstanding Research

Limitations

Researching the limits of LoRaWAN involves investigating the effects on communication reliability and maximum range upon altering the PHY layer factors of the LoRa protocol: spreading factor, bandwidth and coding rate, which are directly correlated to the time on air of the packet.

Some research indicates that protocol bandwidth configuration has the largest effect on communication range, while other work suggests that the spreading factor choice does instead. We conclude that this debate remains unsolved, while other factors such as temperature, humidity, and antennae position are widely understood to affect communication performance.

Along communication range, packet delivery ratio (PDR) is a fundamental metric to determine how well a sensor node in an IoT network is performing. It is defined as the percentage of packets received over the total amount of packets sent by the end device.

Studies have been published analyzing these two metrics in different environments including urban, mountainous, outdoor and rural, as well as indoor. For these, the data content of the packets is usually not as important as the metadata related to the packet transmission, which includes information like SNR and received signal strength indicator (RSSI) at the receiving gateway.

In research by S. Wang *et al.*, "Long-Term Performance Studies of a LoRaWan-Based pm2.5 Application on Campus" (2018), an analysis of air quality on campus ground is carried out, with data sent every 72 s for over 12 months using 22 different nodes with different altitudes and distances from the gateway. Interestingly, devices on rooftops have a lower PDR despite having comparable SNR as devices on lampposts, closer to the ground, suggesting that the SNR is not directly related to the likelihood of a packet being successfully received and decoded. Including additional gateways in the setup, however, results in increased PDR across the whole deployment by about 10 percent.

In "Evaluation of LoRa LPWAN Technology for Remote Health and Well Being Monitoring" by Petäjäjärvi *et al.* (2016), a gateway is placed inside the University of Oulu's campus and a single moving sensor is set up to transmit a packet every 5 s at +14 dBm. The setup is entirely composed of commercially available products, and results show that using the maximum spreading factor of 12 brings a PDR of around 96 percent. The authors found, however, that the packets were only getting sent every 13 s instead of the programmed 5. This is because of the limitations imposed by law on the maximum data rate in the unregulated LoRaWAN frequency bands and ultimately will lead to scalability issues.

In fact, as demonstrated by [3], in deployments with 250 to 5000 devices and 3 available channels, not only are the devices constrained to a transmit time that would not exceed the regulations, but also collisions prevent most of the packets from being successfully received and decoded. Because of this, the PDR reduces to values below 20 percent as the number of nodes increase. The problem of collision between packets was also proven by various researchers making use of mathematical models for signal propagation and software simulations.

RESEARCH CHALLENGES

To answer the reduction in PDR that hampers the scalability requirement of any LoRaWAN future application, M. Cattani *et al*. [4] find that it is best to send data using the fastest and more fragile configuration available rather than increasing resilience and air time while trading off speed. Provided that a retransmission function is implemented to handle missed packets and the configuration is such that the deployment exhibits high enough initial PDR (greater than 20 percent), this should yield the maximum effective throughput. On the other hand, in "Performance Analysis of LoRa Radio for Indoor IoT Applications (2017), E. D. Ayele *et al*. carry out indoor performance analysis at the Twente University Campus and reaches the conclusion that the SF should always be increased to minimize the effect of interference and increase PDR across larger distances. Somewhat similar research is brought forward by A. Hoeller *et al*. in "Exploiting Time Diversity of LoRa Networks through Optimum Message Replication" (2018), where each message is sent a number of times, increasing the probability that at least one of those packets is successfully received and decoded by a gateway. This seems to be particularly beneficial for low density networks.

Another avenue of research toward resolving the issue of scalability and packet collision is to investigate the recently deployed adaptive data rate (ADR) mechanism for LoRaWAN v1.1. While its performance has yet to be fully characterized, its goal is to maximize both battery life and network capacity by dynamically altering SF and transmission power of each node. In "EXPLoRa: Extending the performance of LoRa by suitable spreading factor allocations" (2017), F. Cuomo *et al*. present two different algorithms that can assign different spreading factors to the nodes around a single gateway. Somewhat in contrast with the proprietary ADR, which assigns the lowest possible spreading factor that still yields a good communication link between node and gateway, in their work they aim towards a smart and even spreading factors distribution among the nodes. Due to the SF orthogonality, uplink messages sent with different spreading factor can be received by a gateway at the same time on the same channel, hence eliminating a possible collision. The first approach is based on allocating the full range of available spreading factors (7–12) to all sensor nodes. This involves potentially allocating a higher-than-needed SF to some nodes, but by varying the values, the overall probability of collision should decrease. The second approach is an improvement on the first one, taking into account other metrics such as time on air and balancing spreading factors between groups of potential interferes. The algorithms were tested in simulation and showed an overall increase in PDR against the standard ADR algorithm, especially for densely populated networks with fast data rate.

Generally the consensus is that the scalability of LoRaWAN-enabled applications is limited with current state-of-the-art technology [3, 4, 17]. Part of the problem is the fact that downlink availability is itself constrained by the number of nodes a single gateway services. This prevents time-sensitive applications and also limits the possibility for solutions that rely on the feedback of metrics regarding the communication link from the gateway. As there is no node-to-node communication possible in LoRaWAN, messages between nodes need to be necessarily relayed via a gateway. With gateways subjected to the same duty cycle restrictions as nodes, this could hamper such solutions in a real-life, non-simulated setting.

FUTURE RESEARCH

The following research challenges emerge from the literature reviewed:

- The development of better adaptive data rate mechanisms, based on dynamic spreading factor and other parameters allocation to increase system scalability above the current limits [18]
- The development of retransmission and message duplication mechanisms as an ideal way to deal with collisions and increase PDR as opposed to increasing the spreading factor and time on air [4]
- The reduction of costs and the standardization of hardware and software for LoRaWAN development, which should promote its widespread use

More gateways being online results in an increased downlink capacity for each. This would increase the range of feasible solutions for the issues outlined in this review, all the while reducing collisions [17].

In order to address these issues, several universities and research centers are developing testbeds for development and validation, including our group at the University of Glasgow. The hardware comprises mostly elements purchased through The Things Network (TTN). The Things Network is a community-made website that provides an open source back-end for IoT applications. Three "The Things UNO" nodes are currently set up to monitor air temperature, humidity, and light intensity alongside soil moisture (four variables) for three potted plants, positioned in three different rooms situated on various floors of the University of Glasgow Engineering building, James Watt South. The gateway is also positioned within the building. The vision for this testbed is to expand the number of sensing nodes and gateways to develop and validate different management and data processing algorithms, moving toward adaptive and cognitive implementations that can dynamically self-organize to cope with the network's changing requirements.

CONCLUSIONS

LoRaWAN has been under the spotlight in recent years due to its suitability to be the standard communication protocol for IoT deployments. It provides long communication range and low energy consumption by drastically reducing the avail.able data rate. In this article, the LoRaWAN protocol was briefly introduced alongside some of the agri-tech applications enabled by it. LoRaWAN's limitations were also analysed. The biggest issue to future development of large-scale Lo-RaWAN applications is the effect of packet collision on the deployment scalability. As shown in literature, increasing the number of devices in a deployment with limited gateways drastically reduces the number of packets successfully received and decoded. Duty cycle limitations apply to both sensor nodes and gateways making many of the proposed solutions for packets collision which rely on downlink, such as rescheduling mechanisms or intelligent and dynamic spreading factor allocation, harder to implement or simply not viable.

Many research groups, including the authors', are working on developing LoRaWAN enabled smart agriculture test beds to improve our understanding of the impact of the presented limitations using experimental test data, and moving towards building predictive models and adaptive network management algorithms for smart farming using the data collected.

ACKNOWLEDGMENT

The authors would like to thank the UK EPSRC supporting Bruno Citoni's Ph.D. studentship through grant EP/R512266/1, and to acknowledge the support of the wider Communication

Sensing and Imaging (CSI) research group, School of Engineering, University of Glasgow.

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BIOGRAPHIES

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