# 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% 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 utilise water more efficiently optimising electricity consumption and costs of labour; sensors on plants and soil can optimise 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 (Internet of Things) revolution is then 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 LoRaWAN (Long Range Wide Area Network) enabled IoT application for smart agriculture has been presented. LoRaWAN limitations and bottlenecks are discussed with particular focus on their effects on agri-tech applications. A brief description of a test bed in development is also given, alongside a review of the future research challenges that this will help to tackle.

*Index Terms*—LoRaWAN, IoT, Smart Agriculture, Agri-Tech.

## I. 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 UN 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 is a technological advancement capable of improving efficiency in the global agricultural landscape, accelerating progress towards the goal of increased production. By Internet of Things (IoT) we mean an architectural framework for systems where computing devices including sensors and actuators wirelessly exchange data collected from

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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' collect relevant data with sensors to be transferred and processed remotely and give 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 behaviour and machine status. Smart irrigation systems can for instance utilise 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 optimises resources consumption such as water and energy, as well as cost of labour. 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 to develop sensors, communication protocols, and data processing algorithms that can satisfy all the requirements in the context of future smart farming and be at the same time sustainable and cost-effective.

This articles is structured as follows: an introduction to LP-WAN (Low Power Wide Area Networks) is presented in Section II. A review of LoRa (Long Range) and LoRaWAN is presented in Section III and current state-of-the-art applications for smart agriculture in Section IV. LoRaWAN technology bottlenecks are presented in Section V. Future directions in research are discussed in Section VI, followed by concluding statements in Section VII.

## II. Communication Protocols and IoT

Fundamental to the Internet of Things revolution is the adoption of a communication technology which 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 in providing the required performances 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 which 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
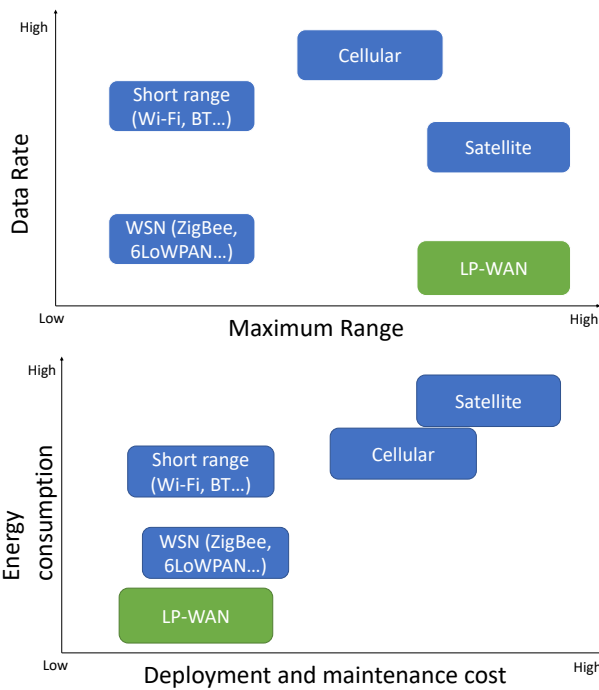
Fig. 1: Comparison of main IoT enabling communication technologies in terms of range, data rate, energy consumption and costs

only relatively few devices to connect to each base station while granting them a 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 sensors applications [2]. Short range communications protocols such as Wi-Fi and Bluetooth suffer partly for the same design flaw of cellular. Although these technology are in use in some agri-tech applications today, they were also designed to handle a higher volume of data than what is required for standard IoT purposes, at the expense of increased power consumption, which is unfeasible for battery powered devices to be used in rural and difficult to access agricultural and natural environment. 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 present challenges when increasing the amount of connected devices past a certain number, without exponentially increasing the network complexity and its power 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.

Low-Power Wide Area Networks (LP-WAN) are a type

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

## III. 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 MAC layer protocol built upon LoRa and its specifications are openly available as well as being endorsed by the LoRa Alliance.

### A. LoRa physical layer

LoRa uses the licence-free, region dependent ISM frequency bands: 863-870 MHz for Europe and 902-928 MHz for the US, but 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% 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 second and a duty cycle of 1%, the sub-band will have a 99 seconds mandatory silence time. This restricts the available air-time per device to roughly 36 seconds per day, which makes LoRa unsuitable for high data rate applications. LoRa devices usually can transmit over multiple channels (defined by different centre frequencies) and utilise channel-hopping algorithms which aim to find the best possible channel to transmit the data on 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 lpwans: 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 which give flexibility to the designer in regards to the maximum achievable communication range and power consumption and data rate.

- Spreading factor (SF), which is related to the number of chirps that are used to encode a single bit on information in the modulation of the message. Larger spreading factors increase the SNR (signal-to-noise ratio) and therefore the communication range, at the cost of slower transmission and longer air-time for each packet.

Depending on the SF in use, data rate ranges from 0.3 kbps to 27 kbps [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 packets length, air-time and energy consumption [4].

### B. 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 are comprised of three main elements:

- Nodes: sensor boards responsible of 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.
- 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 organised 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. Fig. 2 shows an example of topology for an 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 utilised by WSN (wireless sensor networks), where clusters of devices communicate to a sink they have to associate with directly, and which in turn forwards the message on. These multi-hopping 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 bi-directional, so devices can send data to the network via uplink, and receive instructions via downlink. Uplink direction is however strongly favoured. 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.
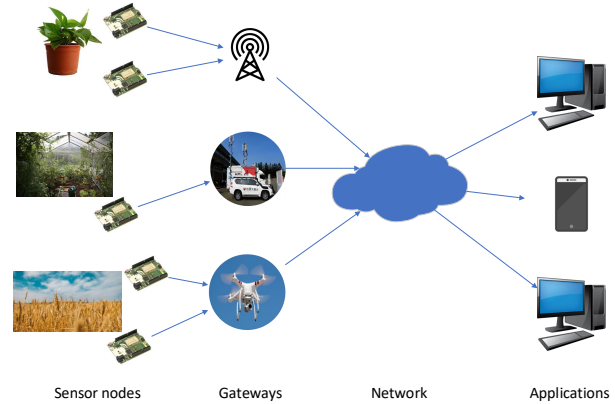


Fig. 2: Typical star-of-stars LoRaWAN network topology

Other custom protocols can be built upon the LoRa PHY layer. LoRaBlink, was developed by [5] to achieve multi-hop, 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].

## IV. 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 Internet of Things (IIoT) applications. In these scenarios only small amounts of data need to be analysed 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: optimising water usage in farming by monitoring soil condition and intelligently activating sprinklers.
- Large and small arable farming: including soil monitoring, chemical analysis for pest 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 test beds for future research, or investigations on the feasibility and performance of the protocol for different use cases. Table I 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 DIY (do-it-yourself) applications ranging from smart gardening gadgets to attempts to automate lawn irrigation. They usually combine LoRaWAN (when at all used) 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 organisations which 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 (10000 to 20000 hectares) makes it so the process of gathering information about the livestock well-being is 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 increasing productivity and security while also reducing the amount of manual work required by the business owners.

Moving forward, it is fundamental to try and grow the community of LoRaWAN users as this will lower the costs associated 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 time-frame and with a reduced capital investment [15], [16].
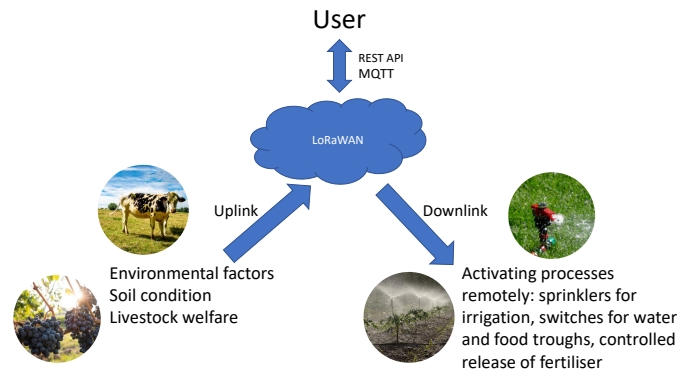


Fig. 3: Typical downlink and uplink contents in LoRaWAN enabled agri-tech deployments.

## V. LoRaWAN: limits and outstanding research challenges

### A. 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 protocol bandwidth configuration has the largest effect on communication range, while other suggests that the spreading factor choice does instead. We conclude 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 analysing 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 RSSI (Received Signal Strength Indicator) 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 seconds 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 lamp posts, closer to ground, suggesting the SNR is not directly related to the likelihood of a packet being successfully received and decoded. Including additional gateways to the setup however results in increased PDR across the whole deployment by about 10%.

In "Evaluation of lora lpwan technology for remote health and wellbeing monitoring" by Petäjäjärvi, et.al. (2016) a

TABLE I: LoRa-Enabled agri-tech applications in literature

| Ref. | Application | Number of nodes | Coverage | SF | BW | Operating Frequency | Payload Length | Payload content | Nature of research |
|---|---|---|---|---|---|---|---|---|---|
| [7] | Drip irrigation control | Up to 4 actuators per node | - | 10 | 125 KHz | 433 MHz | Max. 9 bytes | - | Test bed |
| [8] | Mushroom house monitoring and control | 3 per mushroom house plus actuators | - | - | - | - | - | Temperature, humidity and $CO_2$ | Test bed |
| [9] | Maize crop monitoring | 27 | 648 $m^2$ | - | - | 868 MHz | - | Soil moisture and temperature, light intensity, humidity, ambient temperature and $CO_2$ | Costs and power consumption evaluation |
| [10] | Tree Farm monitoring | - | Up to 200 m | 7 to 11 | 125, 250KHz | 915 MHz | 9 bytes | 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 | 3 sensor nodes and 1 actuator node | 1 km radius | - | - | - | - | Air temperature, humidity, leaf wetness and soil moisture | Proof-of-concept |
| [13] | Water troughs monitoring | 5 physical sensor nodes, 100 simulated nodes | 0.5 to 2.7 km | - | - | 915 MHz | 26 bytes | - | Proof-of-concept |
| [14] | Horse stable monitoring | 1 node | 70 meters | 7 | 125 | 868 MHz | 2 bytes | Temperature and humidity | Use cases analysis |
| [14] | Agricultural land monitoring | 1 sensor buried 10 to 60 cm in soil | 40 to 350 meters | 7 to 10 | 125 | 868 MHz | - | Conductivity and soil temperature | Use cases analysis |

gateway is placed inside the University of Oulu's campus and a single moving sensor is setup to transmit a packet every 5 seconds at +14 dBm. The setup is entirely comprised of commercially available products and results show, using the maximum spreading factor of 12, a PDR of around 96%. The authors found however that the packets were only getting sent every 13 seconds 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 the devices are 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% as the number of nodes increase. The problem of collision between packets was also proven by various research making use of mathematical models for signal propagation and software simulations.

### B. Research Challenges

To answer the reduction in PDR with collisions which hampers the scalability requirement of any LoRaWAN future applications, 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 a re-transmission function is implemented to handle missed packets and the configuration is so that the deployment exhibits high enough initial PDR (greater than 20%), this should yield the maximum effective throughput. On the other hand, In "Performance analysis of LoRa radio for an indoor IoT applications" (2017), E. D. Ayele, et.al. carry out indoor performance analysis in Twente University

Campus and reaches the conclusion that the SF should be always increased to minimise 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 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 packets collision is to investigate the recently deployed ADR (Adaptive Data Rate) mechanism for LoRaWAN v1.1. While its performance is yet to be fully characterised, its goal is to maximise 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 yield 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 as well as limiting the possibility for solutions which 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 gateway subjected to the same duty cycle restrictions as nodes, this could hamper such solutions in a real-life, non-simulated setting.

## VI. 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 re-transmission 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 standardisation 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 centres are developing test beds for development and validation, including our group at the University of Glasgow. The hardware comprises mostly of elements purchased through The Things Network (TTN). The Things Network is a community-made website which provides an open source back end for IoT applications. Three 'The Things UNO' nodes are currently setup to monitor air temperature, humidity and light intensity alongside soil moisture (4 variables) for three potted plants, positioned in three different rooms situated in various floors of the University of Glasgow Engineering building, James Watt South. The gateway is also positioned within the building. The vision for this test bed is to expand the number of sensing nodes and gateways to develop and validate different management and data processing algorithms, moving towards adaptive and cognitive implementations that can dynamically self-organise to cope with the network's changing requirements.

## VII. 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 available 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 LoRaWAN 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 re-scheduling 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.

## ACKNOWLEDGEMENT

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