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A Survey on LoRa for IoT: Integrating Edge Computing

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***Abstract*—Increased automation and intelligence in computer systems have revealed limitations of Cloud-based computing such as unpredicted latency in safety-critical and performance-sensitive applications. The amount of data generated from ubiquitous sensors has reached a degree where it becomes impractical to always store and process in the Cloud. Edge computing brings computation and storage to the Edge of the network near to where the data originates yielding reduced network load and better performance of services. In parallel, new wireless communication technologies have appeared to facilitate the expansion of Internet of Things (IoT). Instead of seeking higher data rates, low-power wide-area network aims at battery-powered sensor nodes and devices which require reliable communication for a prolonged period of time. Recently, Long Range (LoRa) has become a popular choice for IoT-based solutions. In this paper, we explore and analyze different application fields and related works which use LoRa and investigate potential improvement opportunities and considerations. Furthermore, we propose a generic architecture to integrate Edge computation capability in IoT-based applications for enhanced performance.**

***Index Terms*—IoT, Edge Computing, Fog Computing, Smart Cities, Smart Agriculture, Farming, Animal Tracking, IIoT, Smart Metering, LoRa, LoRaWAN, LPWAN, Survey.**

I. Introduction

The number of Internet of Things (IoT) applications has exponentially increased in recent years. Often these require low-power operation and long-range communication which cannot be provided by traditional communication protocols such as Wi-Fi and Bluetooth. Low power wide area network (LPWAN) becomes one of the most prominent candidates satisfying the requirements. LPWAN have been extensively studied over the last decade and multiple protocols related to LPWAN have been developed [1]–[5]. LoRa/LoRaWAN and Sigfox are the mostly used among LPWAN related protocols as they provide very low power consumption and long-range transmission. The main drawback of these technologies is that the data rate is significantly lower compared to Wi-Fi or Bluetooth.

The big data generated by an exponentially increasing number of connected devices has yielded system architectures based on new computational paradigms such as Edge computing [6]. Unlike traditional IoT-based architecture [7] where the collected raw data is sent from end-devices to gateways and then forwarded to Cloud servers, Edge-assisted IoT architecture consists of an extra layer between end-devices and gateways. The Edge layer refers to the action of data processing and analysis capabilities near where the data originates. We emphasize that by leveraging the advantages of Edge computing, end-devices can provide rich information with a limited amount of transmitted data. This lowers the burden of the Cloud servers through a more distributed computing approach, and simultaneously reduces network load.

Low-Power Wide Area Networks (LPWANs) have emerged to overcome some disadvantages of short-range communication protocols (i.e., Bluetooth and Wi-Fi). For example, LPWANs help maintain low-power operation which cannot be achieved with Wi-Fi [8]–[11]. LPWANs also offer a long-range communication up to kilometers. The two prominent protocols of the LPWAN family are LoRa (Long Range) and Sigfox [12]. Sigfox uses narrow-band modulation while LoRa is a modulation scheme which uses chirp spread spectrum (CSS). Different open and proprietary standards for the link and network layers have been designed and some of them can be independently deployed by end-users.

Although there are different protocols in LPWAN family such as *Weightless*, *Ingenu RPMA*, *Symphony Link*, we have conducted a study of recent use cases where LoRa has been applied. We have chosen LoRa, among other LPWAN technologies, because of its market penetration and wide use in the industrial, educational and amateur community. LoRa is a technology that defines a physical layer for low-power and long-range communication, and can be operated on sub-gigahertz unlicensed radio bands. LoRaWAN is the standard protocol for the link and network layers over LoRa backed by the LoRa Alliance. Private LoRaWAN networks can be deployed by individuals or organizations. Among several open and public ones existing across the globe, the Things Network is one of the largest public LoRaWAN networks [13].

Due to the open standard, LoRaWAN has been deployed in many public networks such as the ones in Amsterdam and Bristol [14]. However, from another viewpoint, LoRaWAN cannot be considered as a fully open standard since the LoRa patents are property of Semtech Corporation and only devices manufactured by them can be used for data transmission with LoRa. Fortunately, the LoRa network is open for everyone for professional and non-professional usage. This has boosted the popularity of LoRa in general and particularly LoRaWAN for a myriad of applications related to the IoT.

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Multiple studies on LoRa and LoRaWAN have been published over the past few years [1] [9] [10]. However, the fast adoption of the technology and its increasing adoption by industry and academia demonstrate its applicability in new scenarios every day. Moreover, to the best of our knowledge, previous surveys and studies on LoRa has been focused on its applicability for the IoT in general. This mostly includes applications where lower volume of data are acquired and transmitted over the network. In this paper, in addition to an overview of up-to-date LoRa-based applications, we provide a proof-of-concept (PoC) of an Edge-assisted IoT architecture suiting to high data rate LoRa-based applications while maintaining LoRa and LoRaWAN's advantages of low power consumption and long-range communication. The architecture can open the door to a myriad of new possibilities and scenarios.

The rest of the paper is structured as follows. Section II discusses different applications based on LoRa and LPWAN technologies which would benefit from Edge computing. Section III presents the advantages of leveraging Edge computing in applications that rely on LoRa communication. Section IV discusses aspects which should be taken into account for LoRa-based solutions. Finally, Section V concludes the work.

II. Application Scenarios

In this section, we discuss multiple recent IoT applications based on LoRa and LPWAN and analyze possible enhancement possibilities.

A. Smart Cities

IoT has been closely related to the concept of smart cities [15]–[19]. Mitton *et al.* proposed integration with Cloud services and software as a service (SaaS) platforms. They defined a high-level modular architecture that offers adaptability to a wide variety of sensor data. A variety of sensors is since being deployed in cities across the world to provide city administrators with more in-depth information of the environment and the interaction of citizens with a city's infrastructure [20] [21]. In earlier applications, Wi-Fi, Bluetooth or GSM/3G/LTE were the mainly used wireless technologies, but more recent solutions have been presented that use LoRa for low-rate, low-power, long battery life applications in Smart Cities [12], [22]–[26]. Regarding the reliability of LoRa, Pasolini *et al.* have shown that the range of LoRa in a dense urban environment is about 1 to 2 km, with the gateway deployed in a favorable position at 71 m above average ground level [23]. The authors have run different simulations to estimate the bit error rate, and the percentage of packets successfully received at the gateway for different configurations.

B. Industrial IoT

With the increased variety of applications in industrial environments where connectivity, monitoring, tracking and control are necessary, there has always been a need of a cost-effective solution [27]. In such scenario, LoRa technology has gained popularity due to its small hardware footprint, low-power operation and long range. Addabbo *et al.* [28] proposed a system based on LoRa LPWAN to monitor chemical emissions in industrial plants. The system consists of sensor nodes in which an array of humidity, temperature and electrochemical gas sensors are managed and thus compensates temperature sensor data dependency when monitoring gases such as CO, NO_x and O_2. In addition, a network architecture for acquiring and managing data is presented with tests ensuring that in noisy urban areas it is possible to achieve a communication range of 3 km.

The latest industry standard encourages digitization, computation and use of multi-nodal data exchange. With a time-based channel hopping mechanism of LoRa and specific planning of the parameters such as time, frequency and spreading factor, it is possible to access up to 6000 individual nodes in a minute cycle, as investigated by Rizzi *et al.* [29]. Huang *et al.* [30] shown a simulation that constitutes a multi-hop long-chain topology to analyze and find the optimal path for power lines in smart grids, resulting in greater performance in long-distance transmission.

Waste management from growing industries is a challenge particularly for manufacturing plants and consumer production. Mdukaza *et al.* [31] proposed an IoT-based smart waste management system using LoRa and LPWAN with improvement in usability and performance due to problems caused by weather conditions, unauthorized access, range. Another approach by Chung *et al.* [32] presented a system for intelligent classification and environment monitoring with LoRa. The system focuses on automatic classification, easier monitoring and actuation based on a wide range of sensors for the trash containers and provides historical data from different locations for enhanced garbage collection management.

C. Animal Tracking and Farming

Yim *et al.* deployed an IoT-based crop monitoring system and recognized the LoRa LPWAN as appropriate technology for using in agriculture [33]. They noted that there were inconsistency in RSSI and data reliability during the communication with respect to distance and that LoRa technology is affected by Fresnel Zone. However, they have not shown a clear way of solving those and to improve performance in rural areas where there is lot of interference.

In another work, Ali *et al.* [34] proposed a precision agriculture monitoring system with Green IoT in focus for observing different aspects such as weather, soil, water, pesticide, fire and intrusion from anywhere. The authors considered LoRa as a better alternative compared to other communication protocols such as ZigBee, Wi-Fi and GSM for periodic updating of data while using lower energy. The system is supposed to reduce emission of greenhouse gases and lower the time it takes to deploy such infrastructure in a cost-effective way.

Wireless Sensor Networks (WSN) paved the way to systematic surveillance of wildlife. An interesting attempt was made by Ibrahim *et al.* [35] to better understand the life of Swiftlet birds by using LoRa communication and video analytics with a simulation of optimum condition inside a bird's nest. The proposed system uses LoRa alongside 3G GSM connectivity to monitor temperature, humidity, oxygen level and number of birds going in and out of a particular nest.

Li *et al.* presented a LoRa LPWAN based data acquisition collar for monitoring the vital signs of grassland roaming cows [36]. The system enhances husbandry of animals with the use of sensors such as GPS sensor and accelerometers taking the advantage of long-distance communication of LoRa technology to reduce human labor and related resources. The proposed system consists of different sensor-equipped nodes communicating over SX1278-based LoRaWAN besides gateways and severs.

D. Smart Metering

In an extensive analysis, Tome *et al.* illustrated how event-based monitoring can be used to reproduce a user's electricity consumption profile rather than using the traditional time based monitoring [37]. They used LoRa communication to send the data of which the interval of transmission is reduced because data is sent only when a change in the monitored load is detected rather than continuously sending. The authors have focused on LoRa based meters to send average power requirement to a gateway during a given period. Being event-driven the system is inherently able to detect peak consumption and could reach a 90% similarity with respect to when monitored continuously.

Li *et al.* analyzed water consumption metering system for consumers and presented a multilevel remote meter reading architecture based on LoRa and GPRS [38]. The system relies on three components- a meter node, a repeater and a concentrator which stores the acquired data and then sends it to the server for remote management and monitoring. They also defined an uplink communication data packet format to ensure data integrity and system reliability. However, their proposed system uses multiple communication technologies at the lower level of the hierarchy which could be simplified by using the LoRa as it has longer range and lower power requirement.

Monitoring electricity consumption in a secure and properly managed way is another challenge in developing countries where the digital infrastructure is just emerging and there are a lot of customers. Dalpiaz *et al.* presented an impressive low-cost battery-free power meter based on energy harvesting and LoRa wireless transmission [39]. The authors claim that it can drastically reduce energy consumption due to zero standby energy requirement at zero-load situation as the device harvests energy from the load it monitors and transmits data only when there is a threshold voltage present. This approach reduces the cost of installation, maintenance and eliminates need of replacing batteries.

In another work, Wibisono *et al.* has presented an advanced metering infrastructure based on LoRaWAN for eco-friendly smart grid [40]. As the single phase meters do not require lot of data to be transferred, the authors preferred LoRa communication technology over GSM-based solutions due to its low-power operation, cost-effectiveness and unlicensed frequency band availability. They claimed that the proposed system achieved full control accuracy of the meters while reducing investment and operational cost to 60% and 90%, respectively. The authors discussed how LoRaWAN can still be used under special IoT category in countries where the exact frequency is not available through sub-licensing and compliance certification. However, the system sends all data to a central base transceiver station (BTS) without any processing in terms of compression, encryption and data integrity check which can cause problem when the number of customer increases or when covering large area.

E. Environment Monitoring

Wu *et al.* presented a wearable sensor node named WE-Safe based on LoRa for monitoring levels of carbon monoxide, carbon dioxide, ultra-violet rays and other general environmental parameters [41]. The low-power sensor node connects to a gateway for sending data to the Cloud. However, the proposed system is not feasible when the number of nodes increases. In addition, the authors did not mentioned if any kind of processing is done after receiving the data and how it is handled in situations when the network is not available. The system would benefit from data pre-analysis before uploading the data to the Cloud considering the fact that numerous nodes can generate a huge amount of data resulting in a unpredicted latency and possible bottleneck in the network.

Guibene *et al.* has presented a PoC for monitoring river environment by deploying a buoy with multiple sensors, LoRa LPWAN-based transceiver and a 3G modem [42]. They measured water depth, temperature, velocity and GPS location. The performed experiment validated that it was possible to cover a large area with near-line-of-sight LoRa transceivers. A boundary condition was set to prevent erroneous sensor data when the data bytes got changed due to long distance but were received with a valid CRC. Introducing Edge computing capable gateways before the central gateways and applying compression and appropriate error handling mechanism would improve the system.

In a similar work, Nordin *et al.* has implemented a narrow-band IoT-based hydrological monitoring system for a rural lake marked as UNESCO biosphere [43]. The authors have investigated network performance predictability, limitations and reliability of wireless networks in rural area and with 2G and LoRa. They concluded that GSM-based data communication is not reliable in rural areas due to irregular terrain and non line of sight operation and decided that LoRa is a better alternative in terms of RSSI with high altitude antenna placement.

In summary, although the mentioned LoRa and LoRaWAN-based applications show benefits of long-range communication, these cannot be considered the most appropriate solutions as those are not scalable. When the number of LoRa-based sensor nodes increases significantly and the collected data is large, the system will collapse. Consequently, high latency and data errors may occur due to bandwidth overload or LoRaWAN regulation cannot be fulfilled. Therefore, a new architecture is required which can both harvest advantages of LoRa and provide scalability.

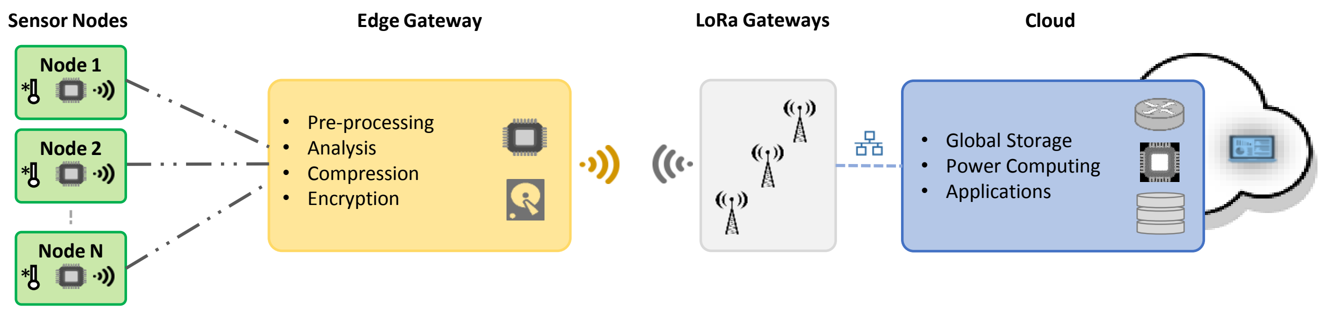

Fig. 1. The proposed system architecture with integration of Edge computing

III. Leveraging Edge Computing with LoRa

Edge and Fog computing is a paradigm which refers to the concept of distributed computing by bringing advantages of Cloud paradigm to the Edge of the network [44]. With this approach, benefits including load-shedding in the Cloud and efficient bandwidth utilization can be achieved. Moreover, by bringing services such as advanced analytics, artificial intelligence and distributed storage closer to end-devices, overall system latency can be significantly reduced.

While Cloud computing has been playing a remarkable role in IoT applications for smart cities, more recently Fog and Edge computing have been leveraged to reduce the network load and the amount of unprocessed data transmission while enabling a more balanced and intelligent solution with distribution of computational tasks across different layers in the network. Perera *et al.* presented the integration of Cloud and Fog computing as a sustainable solution for a smart city to minimize the waste of resources such as network capacity, Cloud storage and computational capability of Cloud servers [45]. A mobile Edge computing architecture has been tested by Chen *et al.* using unmanned aerial vehicles (UAVs) to gather environmental data from different points of a city [24]. In this case, sensors are not static and the drones move towards points of interest to obtain data.

Giordano *et al.* introduced a platform that enables Edge computing for tasks carried out by multi-agent systems [46]. Tang *et al.* presented a pipeline monitoring system with sequential learning algorithms and a prototype for a PoC [47]. The authors also introduced a hierarchical Fog Computing architecture for big data analysis in smart cities [48]. The advantages of adopting Edge computing in a smart city environment have been studied by He *et al.* in an extensive framework that enables organization of computing, networking and caching resources to enhance the performance of different applications [49]. Improving the quality of service (QoS) with mobile Edge computing (MEC) by realizing the 'Follow Me Edge' concept has been addressed by Taleb *et al.* [50]. The proposed MEC network architecture has ultra-short latency. Suresh *et al.* [51] presented an architecture based on LoRa for monitoring animal health. Machine learning is applied at Edge device for data compression and feature-extraction and then sent via LoRa to gateway for forwarding to Cloud servers. The experimental results show that the proposed approach helps to extend the battery life of sensor nodes from 13 to up to 39 days.

As illustrated in Figure 1, we show a PoC of an Edge-assisted IoT applications using LoRa and LoRaWAN. The proposed architecture is different from the Edge-assisted or Fog-based papers mentioned above. In addition to traditional IoT architecture, the proposed architecture consists of an extra layer of Edge-assisted gateways. In detail, sensor nodes can collect different information and transmit the data over Bluetooth Low Energy (BLE), nRF, or IPv6 over Low-Power Wireless Personal Area Networks (6LoWPAN) to a Edge-assisted gateway. The Edge-assisted gateway is often equipped with a high-computation capable hardware, fixed in a place and uses socket power or a large battery. Therefore, the Edge-assisted gateway is able to perform complex algorithms while maintaining its operation for a long period of time. These protocols can transmit data with a data rate up to 250 kbps in theory and 150 kbps in practice [52], [53] while they consume approximately 70 mW of power. Correspondingly, these are suitable for high data rate applications such as real-time ECG monitoring. When the number of sensor nodes increases significantly, extra hardware modules (i.e., nRF, 6LoWPAN or BLE) can be added into one or several Edge-assisted gateways depending on the application. In case when an application requires extremely high data rate such as video streaming, Wi-Fi can be used as the main wireless communication between sensor nodes and Edge gateways. However, this results in an increase in energy consumption of sensor nodes.

At Edge-assisted gateways, data can be compressed by lossy or lossless algorithms depending on the application. The lossless compression does not provide high compression rate as possible in lossy ones such as approximately 10:1, but the data can be correctly decoded without compromising any information. It is suitable for critical applications such as real-time health monitoring whilst lossy one suits to non-critical applications such as video streaming. The compressed and summarized data is sent from an Edge-assisted gateways to a LoRa gateway which helps to utilize bandwidth efficiently [54]. In addition, data can be processed at Edge-assisted gateways for extracting useful information which will be transmitted to LoRa gateways for saving bandwidth. In this

TABLE I
DURATION OF ENCRYPTION AND DECRYPTION IN 8-BIT MCU AT 8 MHZ

Scheme	Encrypt (mS)	Decrypt (mS)	Scheme	Encrypt (mS)	Decrypt (mS)
AES-128	0.984	1.312	SECP160R1	1323	1317
AES-192	1.176	1.592	SECP192R1	2158	2165
AES-256	1.384	1.864	SECP224R1	3213	3222

paper, we demonstrate a few features such as data compression and data encryption at both sensor nodes and Edge-assisted gateways.

In our experiments, data is encrypted at a sensor node based on an 8-bit AVR mirco-controller. Then, the encrypted data is decrypted at an Edge-assisted gateway for processing. The processed data is compressed with a lossless LZW algorithm at an Edge-assisted gateway implemented upon a Raspberry Pi 3 before being sent to a LoRa-based gateway. As seen in Table I, latency varies depending on the encrypted algorithm. Depending on the application, a specific encryption algorithm should be chosen. At our Edge-assisted gateway, it took approximately 13.2 ms for compressing 3800 bytes of data and the data compression rate is about 4 times. The results show that Edge computing helps to save bandwidth significantly at the cost of slight increase in latency.

IV. CONSIDERATIONS

Development of traditional IoT solutions widely rely on wireless technologies such as Wi-Fi or Bluetooth, and have client-server models with a strong dependency on Cloud servers. When using low-power, low data-rate solutions such as LoRa, some aspects need to be taken care of which are not commonly addressed.

A. Regulatory Issues

Most of the LPWAN technologies relying on unlicensed free-to-use ISM radio bands have regional or country-specific regulatory limitations. Although bandwidth and spreading factor can be configured to achieve different modulation, LoRaWAN is still limited to a single carrier frequency for a given transmission. For European Union, section 7.2.3 of the ETSI EN300.220 standard states the maximum radiated power limit, channel spacing, spectrum access and mitigation requirements for unlicensed frequency bands [55]. In Europe, 868.0 MHz frequency is commonly used for LoRa. The 868.0 MHz to 868.6 MHz band has a maximum radiated power limit of 25 mW and a maximum duty cycle of 1%. It significantly limits real-time transferable amount of data. This ensures a fair network usage and hence a large number of devices can connect to a single access point. The modulation directly affects range and thus the distance to the access point limits maximum attainable data rate.

B. Security and Reliability

Reliability is an important feature of wireless communication protocols. A reliable protocol needs to fulfill requirements of low error rate and robustness against interference and packet collision. QoS ensures that the communication is predictable, i.e. delays and variation in delay during data transfer are managed properly. Besides, environmental factors and spatial location can affect the performance of the communication. For example, interference from nearby overhead power-line and high-rise buildings can reduce the range and increase packet error rate (PER) [56]. Therefore, a set of situation-aware QoS management rules should be implemented and proper authorization, data integrity verification and recovery plan be applied in cases where errors cannot be avoided completely.

In LoRaWAN protocol, the security needs to satisfy the criteria of LoRaWAN such as low cost, low installation and implementation complexity and low power consumption [57]. Therefore, AES-128 [58] is used in LoRaWAN. Although LoRaWAN does not support originally, it is recommended that AES-192, AES-256 or other lightweight cryptography algorithm based on elliptic curve digital signature (ECDSA) be considered for applications requiring secure end-to-end data transfer. These provide a stronger data authentication compared to an error-detection code or simple check-sum. However, using these algorithms can cause some extra overhead of latency and energy consumption.

V. CONCLUSION AND FUTURE WORK

In this paper, we presented a general discussion of LoRa wireless communication technology and its advantages and limitations. We enumerated different application scenarios which use LoRa to achieve agile, low-power and cost-effective communication to adopt newer practices and standards ranging from Industrial operation networks to simpler IoT-based infrastructure. In addition, important aspects such as regulatory bindings, communication range, security and power optimization were also considered for optimizing the parameters while keeping reliable performance as the goal. Furthermore, we have investigated how different applications could benefit from implementing Edge and Fog computing paradigm which currently use LoRa. In addition, we provided a PoC of an Edge-assisted IoT architecture using LoRa. Data compression and encryption demonstrated via the experiment accredits that the proposed architecture can provide a robust solution for overcoming some of the drawbacks of the existing LoRa-based IoT applications. In future, more services will be applied, demonstrated and analyzed via the experiments in specific applications such as smart home monitoring systems. In summary, LoRa communication technology together with Edge computing can bring a promisingly positive influence on IoT-based applications in boosting operational performance and energy efficiency whilst maintaining reliability and security of the system.

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