LoRa - A Survey of Recent Research Trends

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Abstract - **Nowadays the Internet of Things (IoT) is one of the most promising application areas in information technology for future products and services. Therefore, it is not surprising that new technologies arise, which are marketed as "the most useful technology" for applications in IoT devices. In this study, we focus on the new communication technology called LoRaWAN. Our aim is to evaluate the usefulness of LoRaWAN technology in the field of IoT, and especially in sensor network solutions. The research methodology is a literature survey and primary articles were selected by means of a systematic literature review. More than fifty suitable research papers were identified. From these, the following research questions were formulated: "How to categorize LoRa research papers?" and "What are the application trends in LoRa?" This study presents a way to categorize research papers with diverse themes. In addition, this survey reveals the most recent trends in research and practical applications of LoRa. Finally, this study will give recommendations for researchers and practitioners on how the advantages of LoRa-based technologies could be fully exploited in the development of IoT systems and solutions.**

Keywords - Internet of Things (IoT), Wireless Sensor Networks (WSN), LoRa, LoRaWAN

I. INTRODUCTION

Wireless Sensor Networks (WSN) have developed at a fast pace in recent years and have also been one of the major focuses of research in wireless technology. This rapid development has been facilitated by the evolution of electronics miniaturization, growth in performance, wireless technologies, energy efficiency, and the development of protocols. The sensors that collect environmental information from the surroundings have been miniaturized thanks to the fast performance, optimization, and miniaturization technology of the hardware. The developments of new wireless communication technologies and falling prices have enabled brand-new uses for wireless sensor network devices.

This study is part of the WSN research series. Our former studies [1-4] focused on different topics under WSN. The present studies are performed in collaboration between the Tampere University of Technology in Finland and Keio University in Japan. The aim of this research is to be a review of LoRa studies.

This study introduces one Low Power Wide Area Network (LPWAN) technology – LoRa®. This technology is a rising technology for the transfer of data in implementing sensor network solutions for sensor data collection and transmission from end nodes to base stations. The objective of this study was to find out the usage of this new technology by mapping the current state of the art in the use of LoRa. During this research we first defined the research questions that we wished to resolve. Thus, we sought answers to the following research questions:

RQ1: How to categorize LoRa research papers?

RQ2: What are the application trends in LoRa?

To answer these questions, we performed a comprehensive literature study. We used the Systematic Literature Review approach (SLR) [5] to collect primary studies regarding this research scope. The main phase was to classify the papers and the selected primary studies were then analyzed and categorized using the content analysis method. The results of the classification were five main categories: Analysis, survey and factual discussion, Performance and technical evaluation, Real deployments with prototypes, Simulation, and finally Applications.

The structure of this paper is as follows: In Section II, we review LoRa technology and its main features. In Section III, we introduce the research approach used in this literature study. In Section IV, we present the analysis of the findings and categorization of studies. Section V includes a discussion and suggestions for future research on the topic and finally, Section VI summarizes the study.

II. LORA TECHNOLOGY

In this section, we present the basic concepts of LPWAN, LoRaWAN, and LoRa technologies followed by an introduction to the LoRa and LoRaWAN systems. This technical section is based mostly on "A technical overview of LoRa ® and LoRaWAN ™" [6].

LPWAN are designed to allow wide-area connectivity for low power at a low bit rate [7]. These features meet the requirements of Internet of Things (IoT) applications, such as sensor nodes that work with batteries. The common LPWAN technologies include LoRa/LoRaWAN, Sigfox, and NB-IoT. Fig. 1 characterizes the typical parts and architecture of an LPWAN network. The sensor nodes, an edge node or an end node, collect one or more measured values and then send the data to the base station. The base station transmits the data through the backhaul gateway to some Internet cloud service. The end user or clients can use the collected data from cloud services.

The advantage of LoRa lies in the technology's long-range capability. A single base station can cover hundreds of square kilometers, but the range is highly dependent on the environment or obstructions.

LoRa modulation is based on spread spectrum techniques and a variation of the chirp spread spectrum (CSS) with integrated forward error correction (FEC). It operates in the lower Industrial, Scientific, and Medical (ISM) bandwidths (USA: 915MHz, EU: 433MHz and 868MHz). The LoRa modulation can be utilized by many different protocol architectures such as Star, Mesh, and 6lowPAN. Furthermore, the LoRa Alliance has standardized the MAC protocol called LoRaWAN. LoRaWAN (Fig. 2) defines the communication protocol and system architecture for the network while the LoRa physical layer enables the long-range communication link. The edge nodes of the LoRaWAN network can transfer data to multiple base stations. LoRaWAN is an open standard governed by the LoRa Alliance and the first version, 1.0, of the LoRaWAN specification was released in June 2015. Version 1.1 of the LoRaWAN specification was published in 2017.

LoRaWAN ensures data rates from 0.3 kbps up to 50 kbps, which are considered acceptable for transmitting real-time sensor data in the IoT, Machine-to-Machine (M2M), smart city, and industrial applications. However, transmission of real-time image data, or anything that requires high bandwidth, that may not be suitable on LoRa networks. This low data rate ensures the low power consumption of the edge node devices, therefore enabling the usage of battery for a seamless deployment.

Edge node devices can be configured with different features. LoRaWAN defines three classes of devices. These device classes can negotiate network downlink communication latency versus the battery lifetime. These classes are shown in Fig. 2 and, depending on the application needs, A, B, or C class can be chosen.

Battery-powered devices in "Class A" are intended for low powered devices such as sensors. These are the most energy efficient class but have the biggest latency time. It also includes devices that do not need to transmit data all the time. All the LoRaWAN-capable devices must support the functionalities of this class.

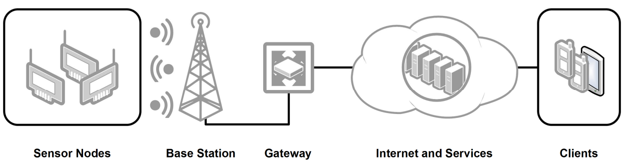

Figure 1. The communication protocol and system architecture of LoRaWAN [6].

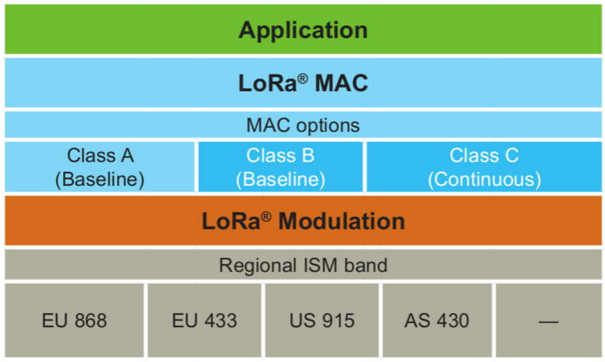

Figure 2. The communication protocol and system architecture of LoRaWAN [6].

The B Class is focused on battery-powered devices, such as actuators and sensors. These are energy efficient but with a latency-controlled downlink. The communication is slotted, synchronized by an external beacon, which allows the server to know when the end device is listening.

The C Class is used by bi-directional end devices with maximal receive slots. The end devices of Class C have almost continuously open receive windows, which are only closed when transmitting. These devices should be used with external power source, are capable of listening to the air interface the whole time, registering no latency over the receive or transmit mode.

LoRaWAN network protocol security is based on IEEE 802.15.4, and is also extended by using two session keys: a network session key and an application session key. Each LoRaWAN edge node device also has its own 128-bit AES key, known as the AppKey.

III. Research Approach

The above-mentioned research questions, RQ1 and RQ2, were formulated when we studied the targets of this research. To answer these research questions, we decided to perform a literature study in order to map the extant knowledge on this domain. We decided to use the SLR method to collect the relevant primary studies and followed the guidelines given by Kitchenham and Charters [5].

For the SLR, we decided to do an electronic search. The databases used were IEEE Xplore Digital Library (IEEE), Multidisciplinary Digital Publishing Institute (MDPI), Association for Computing Machinery Digital library (ACM), ScienceDirect, and others (Google Scholar and similar). All of these databases: IEEE, MDPI, ACM, and ScienceDirect, have their own search engine, but we also used the Google Scholar search engine, the results of which are under the heading "Others", unless the result directed us to databases mentioned before. The survey was started by selecting the main search term: "LoRa". The second search term was "IoT," "LPWAN," or Wireless Sensor Networks." So, the search sentence was: ("LoRa" AND "IoT") OR ("LoRa" AND "LPWAN") OR ("LoRa" AND "Wireless Sensor Networks"). We decided to use these simple keywords in order to obtain good coverage of potential primary studies. The targeted amount of related studies was about fifty, because this amount would give us enough information for categorization and research trends.

In the second phase, we created several reasonable categories and classified the papers into those categories. The reason for this classification was that most of the papers published were relatively distinctive in terms of the research objective, methodology, and application. For the sake of simplicity, we created five categories of papers without ignoring the variations of themes. This way, we systematically examined the details of research papers that fell under the same category whereas too many categories would have made it difficult to compare the trends or research methodology logically. In this phase, we also made a selection of studies so that no single category became too dominant. The total number of suitable papers collected was 54. Please note that some of the papers could be classified into more than one category.

The research categories, and the total number of selected studies are as follows:

- Analysis / Survey / Factual Discussion – 7 papers
- Performance / Technical Evaluation – 29 papers
- Real Deployment / Experimental / Prototype Implementation – 37 papers
- Simulation / Modeling / Networking Stack / Software – 8 papers
- Applications – 20

In the remaining sections of this paper, we will first present the categorization of key studies (in Section IV). This is followed by a discussion section where the presented research questions will be answered.

IV. RESULTS

This section describes the relevant characteristics of each category. The next subsections present all five main categories. At first there is short description of the category followed by a discussion of relevant papers and findings from them. Some of the selected studies have a wider content and therefore the [8-11] studies were classified into three or more categories. The structure of these frequently occurring papers is first, the required technology of the application system is explained, then the system is designed and realized. Finally, the study presents the efficiency tests of the application.

These studies were selected because of the use of LoRa technology. During the processing, we tried to find the answer to a further question – Is LoRa the only possible technology to use? In some cases, the usage of LoRa is not the main focus of the study. There might also have been some other technology instead of LoRa. Because there are several possible technologies, the main result from these categories may also be the answer to the question: When to use LoRa?

A. Analysis/Survey/Factual Discussion

This category consists of research studies where the main part of research is the introduction of LoRa or LoRaWAN technology. In addition, these studies handled technology-based issues such as architecture and protocols, the functional components of the technology, the performance of the technology, and the security issues such as possible vulnerabilities. Most of the research studies also included a comparison with similar technologies.

The studies [8, 12-17] commonly highlight the general background of LoRa technology. These technology reviews summarize the A, B, and C classes of LoRa devices, the LoRa network architecture, and the LoRa network protocol stack.

Moreover, in [13], LoRa technology was compared exhaustively with other LPWAN technologies in terms of architecture, battery lifetime, network capacity, device classes, and security, where the LoRaWAN protocol is 3 to 5-fold more advantageous than Sigfox, NB-IoT, and LTE-M. In a more explicit survey, [16] provides a comparative analysis on LoRa and NB-IoT, claiming that there is no LPWAN technology that fits all requirements, but both LoRa and NB-IoT could be advantageous based on their appropriateness to the system requirements and features they could offer. This analysis shows that unlicensed LoRa has advantages with regard to the battery lifetime, capacity, and cost while the licensed NB-IoT offers advantages in terms of Quality of Service (QoS), latency, reliability, and range.

Interestingly, the security issues in LoRa were mentioned repeatedly in several studies, even though LoRa provides two layers of security, one for the network and another for the applications [12, 13]. The study performed by [14] investigates the potential security vulnerabilities in LoRa by analyzing the LoRa network stack and shows the possible susceptibility of LoRa devices to various malicious attacks. For instance, the analysis demonstrates that, simply by using a commercial off-the-shelf LoRa device, the physical layer can be vulnerable to interference due to the similar frequency and the spreading factor, which may expose the LoRa network to jamming attacks.

B. Performance/Technical Evaluation

This category deals with the wide variation of performance testing in which most studies present the real deployment of LoRa in a test environment. LoRa technology was mostly the key technology in the experiment. Typically, the study used LoRa technology to test some technological features, for example, the scalability of the network was tested in many studies [10, 18, 19] and the QoS was tested with prototypes in two studies [20, 21].

This category also includes several studies focused on testing the suitability of LoRa together with some other technology. These kinds of tests presented LoRa together with the Distribution Management System (DMS) [22], and with i-Car data gathering from the vehicle diagnostic system [23]. LoRa signal propagation was tested indoors [24, 25] and outdoors [26-28]. Mostly these were measured using the packet delivery ratio. Also, the issues of signal interference in LoRa within license-free ISM radio bands were discussed [11, 19, 29].

C. Real Deployment/Experimental/Prototype Implementation

This category consists of the wide variation of prototypes used by LoRa technology. The main idea of the category is that some kind of device has been built and used to collect research-related data. These studies present the deployments of LoRa or LoRaWAN implemented for an application of IoT in different kinds of systems. Mostly this application collected environmental sensor data [30-33]. Tracking applications were also presented [27, 32, 34, 35]. This category includes a few industry-specific prototype demonstrations such as a low-cost device for fault location in Medium Voltage power cables [36]. The reasons why LoRa technology was selected were low power devices with batteries or solar power [30, 37]. The most commonly used hardware was Semtech LoRa module with Arduino or Raspberry Pi.

D. Simulation/Modeling/Networking Stack/Software

This category handles Simulation/Modeling/ Networking stacks/Software. The most commonly used research method was simulation when one or more LoRa technology issues were tested. Normally, the actual device deployment was not fully implemented in this category. Typical simulation test cases were tests where a large amount of simulated devices and connections were tested with some program. Modeling used the same technique. Some of the network configurations were modeled by software without any real devices. Research related to networking stacks typically used the network protocol and included some special software combination which was tested or simulated.

The simulation research studies [11, 18] simulated the presence of a number of end devices. Likewise, [10] simulated the count and diameter of end devices where the coverage of probability dropped when using the same spreading sequence.

E. Application

Under the category of applications, we tried to identify the trends and variations of LoRa applied in real settings. Despite the various thematic applications, many targeted applications aimed to use LoRa as a long-range communication interface for real time monitoring.

Reference [38] used LoRa in their plug and play platform for monitoring the temperature of the blood fridges at a provincial center coordinating a blood transfusion service. Another healthcare application was described in [25]. In contrast, [39] used LoRa for a sensor node powered by vibration from an electromechanical energy harvester on a real bridge to monitor road conditions, such as the temperature of the asphalt and the presence of water or rain. Reference [40] aimed to monitor and control the temperature and humidity of different rooms, with the aim of reducing costs related to heating ventilation and air conditioning. Meanwhile, [30] presented real-time air quality monitoring using various gas sensors.

In references [31, 33], LoRa was used in sensor nodes to detect and prevent a destructive landslide. In a similar way but in a unique application, LoRa has been used to monitor the environment of sea and sailboats, including the speed and direction of wind and current, the location and orientation of the sailboat for sailing sports and races [32]. Reference [35] demonstrated a method of using LoRa for geo-location tracking without requiring GPS. Even though the specific target to be tracked was not clearly demonstrated, it showed great potential for various geo-location tracking applications, such as tracking animals or elderly people. Reference [27] demonstrated a whole object tracking system where the majority of components were implemented: the tracking device communicated with the gateway device using LoRa; the tracking data was collected in the database server, and users had an application for retrieving the data from the server. Reference [23] used LoRa in gateways targeting a vehicle diagnostic system for driving safety.

We found that LoRa has great potential for deployment in a physical environment both indoors and outdoors, whether as the interface for sensor nodes or the gateway. The results of this survey prove the universal application prospects of LoRa. Applications are diverse, ranging from monitoring in healthcare, tracking, environmental monitoring, to structural health monitoring.

V. Discussion

The aim of this study was to evaluate the current state of the art in the use of LoRa-based technologies. The analysis is based on the collection of LoRa-related studies. The amount of studies was large, and the size of this study was limited. The amount was so large that some of the references were only mentioned in passing. However, the conclusion is that this collection of studies has potential for a more comprehensive analysis. This study shows that there are significant different ways to benefit from LoRa technology.

There are several key points peculiar to the LoRa wireless system. This literature review brings out the main benefits of using LoRa technology, namely the long-range communication from 10 to 15 kilometers in an outdoor environment, and the very low power consumption that enables the use of batteries. Of course, these features have a trade-off with other performance factors such as data throughput, which is low compared to, for example, Wifi or Global System for Mobile Communications (GSM) networks. Several studies show that there are still issues surrounding the practical security aspect of using LoRa. Several studies also simulate the limitation of the count of LoRa nodes. They show that one base station could handle a thousand nodes without significant problems related to reliability, such as collisions.

Based on our survey, the papers reviewed under category A provide a useful review for researchers and developers before adopting LoRa in their system by understanding how LoRa technology differs from legacy technology. This provides practical guidelines on deciding whether it perfectly matches the requirements of the proposed IoT system or not while recognizing future assessments in security.

From the survey of papers under category B, some papers present the common objectives of experimental evaluation using various LoRA devices. Most of the research work adopted the experimental evaluation method. Reports from these studies provide a reliable empirical basis of LoRaWAN performance, especially on how LoRa works in a real environment and how various environmental factors affect its performance. This constitutes a significant preparation toward real implementation.

Meanwhile, papers in category C demonstrate the real implementation of prototypes using LoRa. All this research could provide insights on developing a real IoT system based on LoRa, especially on how LoRa works as a prototype in various applications under various conditions.

In category D, even though most of the research studies do not involve the deployment of real LoRa devices, there are many research problems related to large-scale networks that require research methodology based on simulation and modeling, as well as software. For instance, research on dense LoRa networks or the remote control of a LoRa device based on a Software Defined Network (SDN) may be interesting research topics.

The classification of studies in the application areas in category E gives us more insight into the diversity of LoRa applications and the trends of the future research direction. Smart city applications through real time monitoring of environmental and structural parameters or tracking have been highly attractive to date. These applications might be interesting for future research because there was a wide variation in smart city prototype studies. During this study, we observed 12 monitoring/tracking and 8 smart city papers which are included in the source material of this study. This is quite a significant amount. We also believe that there are more prototype projects using LoRa that remain unreported or ongoing.

As far as future work is concerned, we will exploit the results of this survey to devise new research studies with the aim of more practical IoT solutions using LoRa technology. Now that the research and technological bases have been clarified, we can continue to develop devices and systems that use these findings. The results of the RQs raised several new research topic ideas, one of which is sound volume measurement. During Pori Jazz, an international music festival held in the Satakunta region, it would be interesting to measure the sound volume from different places. The main idea is to test the suitability of LoRaWAN technology to transfer measurement data. In addition, because the LoRa technology has no significant limit regarding the count of sensor nodes, it would be interesting to deploy a low-cost distributed sensor network around the area of the Pori Jazz festival.

VI. SUMMARY

In this survey paper, we presented a comprehensive review on the most recent trends in the research and practical applications of LoRa technology. We systematically reviewed the most recent research papers related to LoRa covering a wide variety of research themes, objectives, and methodology and proposed a new method of classifying the research papers into several categories.

Based on the number of publications in each category, we can see that the recent research trends in relation to LoRa concern performance and technical evaluation, as well as real deployments through prototype implementation and experiments with LoRa technology. It could be stated that, currently, research on the technical evaluation and real deployment of LoRa is a hot research trend. This might be due to the high demand for real implementation of LoRa in various IoT projects. However, we also recognize the importance of the simulation/modeling/networking stack and software-based research related to LoRa. We expect that research in this direction will gain much more attention in the near future since the implementation of IoT systems not only involves the networking of LoRa, but an end-to-end system development up to the application layer, involving LoRa as one of the major networking elements in the IoT ecosystem.

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