Designing Energy Harvesting-Low Power Wide Area Networks; A Feasibility Analysis

Original Citation:
Designing Energy Harvesting-Low Power Wide Area Networks; A Feasibility Analysis / Sherazi, Hafiz Husnain Raza. - ELETTRONICO. - (2018). [10.60576/poliba/iris/sherazi-hafiz-husnain-raza_phd2018]

Availability:
This version is available at http://hdl.handle.net/11589/161038 since: 2019-01-18

Published version
Politecnico di Bari
DOI:10.60576/poliba/iris/sherazi-hafiz-husnain-raza_phd2018

Department of Electrical and Information Engineering
ELECTRICAL AND INFORMATION ENGINEERING
Ph.D. Program
S.S.D. ING-INF/03 – TELECOMMUNICATIONS

Final Dissertation

Designing Energy Harvesting-Low Power Wide Area Networks; A Feasibility Analysis

---

by

SHERAZI Hafiz Husnain Raza

Supervisors:
Prof. Luigi Alfredo Grieco
Prof. Gennaro Boggia

Coordinator of the Ph.D. Program:
Prof. Luigi Alfredo Grieco

Course n°31, 01/11/2015-31/10/2018

Department of Electrical and Information Engineering
ELECTRICAL AND INFORMATION ENGINEERING
Ph.D. Program
S.S.D. ING-INF/03 – TELECOMMUNICATIONS

Final Dissertation

Designing Energy Harvesting-Low Power Wide Area Networks; A Feasibility Analysis

---

by

SHERAZI Hafiz Husnain Raza

Referees:

Prof. Ivana Podnar Zarko
Dr. Nicola Accettura

Supervisors:

Prof. Luigi Alfredo Grieco

Prof. Gennaro Boggia

Coordinator of the Ph.D Program:

Prof. Luigi Alfredo Grieco

Course n°31, 01/11/2015-31/10/2018

To my parents, whose sacrifice in every aspect of life enabled me to execute as best as I could. They have all the way been behind me through their prayers to encourage me fulfilling the necessary requirements during this tedious process, making me more energetic and enthusiastic to successfully ending up this work in order to complete my PhD program and to get an opportunity to see you people again after many years.

To my dearest wife for all her support and prayers for ending up this work in a graceful way. It would not have been possible for me to achieve these goals without her caring support and love throughout the journey. She has been very much supportive whenever I was desperate or found myself hopeless in the dark patches, during all the way to destination. She sacrificed her time, luxuries, and several loving relations for letting me step forward in my life. I hereby acknowledge, I could not offer you the time, care, and the comforts you deserved for, because of my busy schedule and hard deadlines.

To my brothers and sisters, whose financial, moral, and ethical support has never let me divert my attention to anything else that might lead me astray somewhere far away from where I am standing today. I have always been thankful to them for their supporting behavior throughout my academic carrier even when I was quite young having a limited domain of knowledge. They paved my way to excellence through their prayers, enlightened thoughts, and broader vision that they had gained with time.

Acknowledgements

Here, I would like to acknowledge some important people, who have continuously been a source of courage and inspiration to accomplish this work and towards achieving my short and long term milestones throughout this doctoral period.

First of all, my supervisors, Prof. Ing. Luigi Alfredo Grieco and Prof. Ing. Gennaro Boggia, who always helped me out not only in putting the curriculum activities on the right way but also supported me through several logistic matters when I arrived here, in Italy, in a completely new environment with different spoken language. They also helped me out learning the real way how an early career researcher should take a step forward, including the identification of my PhD theme. I am thankful to them for the mistakes they have pointed out which have been a source of continuous and quick learning for me during these days. Here, I acknowledge that it could not have been possible without their selfless support and availability round the clock. I admire the way they obliged me offering their valuable time and suggestions whenever needed.

Since I was initially in Padova where I was received by Prof. Michele Zorzi, Department of Information Engineering, University of Padova. Prof. Zorzi was a kind, humble, and sympathetic personality who not only received me warmly, but also played his role to make my connection to the Telematics Lab. I could never forget his role and input in the consultation to make my decisions easier when i was in confusing circumstances. I also acknowledge him for everything he could offer during my early days in Padova.

I would also like to thank my colleague, Dr. Giuseppe Piro who thoroughly guided well to accomplish different research activities to achieve multiple

short term milestones. I always found him courteous and ready to help others whenever he was requested.

During this period, I got an opportunity to visit School of Engineering, University of Glasgow, UK for a short period under the supervision of Prof. Muhammad Ali Imran. Prof. Imran is really an inspiring personality and fantastic human being. He supported me with every possible way, from officially supporting my exchange application to helping me out with finalizing the research directions carried out during my stay in Glasgow. I visited him frequently but he never felt a single sigh of tiredness. Instead, I always found him ready for my guidance and kind sympathies. Only thanking him, seems a formality and not the compliments he deserves, but I am sure about his actual reward by Almighty for his exuberant personality.

Grabbing this opportunity, I also acknowledge the selfless support and encouragement of all my teachers throughout the academic career. Especially, Mr. Arif Bhatti, Mr. Syed Ahmad Hussain Zaid, two senior teachers from my high school, Mr. Javed Iqbal, Mr. Yousaf Ibrahim, from my collage days, and then my instructors at COMSATS University, Prof. Nadeem Ghafoor Ch. and Prof. Saqib Rasool Ch., to name a few among an exhaustive list of names who contributed altruistically to make it happen. They have always been cooperative during these years of higher studies to make me learn as best as they could. They not only practically helped me out but also supported me morally with their ongoing prayers during these years.

Last, but not the least, I am also indebted to the Reviewers, Prof. Ivana Podnar Zarko and Dr. Nicola Accettura, for their encouraging comments and useful suggestions which made it possible for me to improve the quality of this thesis

It was really a wonderful experience working here at Telematics Laboratory in such a cooperative environment where all the colleagues around me were amazing and their behavior made the things easier to look forward with every passing day at POLIBA.

Thank You all.

Husnain Sherazi

Contents

List of Figures

List of Tables

Introduction: Dissertation Overview

In Layman's term "wireless communication" often refers to either Wireless Fidelity (Wi-Fi) or cellular data connections we have these days. Each of them can fit in for a variety of use-cases based on what we need. For example, Wi-Fi enables its users to receive a large amount of data like watching a film from the comforts of their home, within a local area (small vicinity) and for a relatively low cost that is spent as a monthly fee or modem charges. Similarly, with the advancement in cellular infrastructures, cellular connections (such as, 3G or 4G/LTE) can almost do the same for a relatively broader geographical area but for the higher costs in terms of monthly data bundle being subscribed on the top of the mobile price. With the revolution of Internet of Things (IoT) paradigm, the transition of conventional cities into smart cities is inevitable where the technological shift has to lead the transformation of communication phenomenon from personal to Machine-to-Machine (M2M) communication where billions of interconnected objects would be communicating with each other to contribute in an overall smart environment.

Let's assume a smart environment where a user reaches back home, and his car automatically starts communicating with the garage for opening up the door. Once inside, the temperature conditions are already adjusted according to his preference, and a lower intensity light is on in his chosen color for the relaxation, looking at the pacemaker data that indicates the day has been stressful. Acquiring this kind of services requires technologies different than Wi-Fi or cellular networks, that leads to the inception of Low Power-Wide Area Network (LP-WAN).

LP-WAN are targeting the niche in a broad range of IoT applications where long radio coverage is required on the cost of extremely low bit rate support in an energy constrained environment where the message frequency is not reasonably higher. A plenty of contesting candidates have already been marked their entry into the market with some of them floating since 2009. At that time, the number of connected objects was relatively small. The Wireless Local Area Network (WLAN) (e.g., Wi-Fi) and Personal Area Network (PAN) (such as, Bluetooth) technologies had created their hype around IoT so it took some time for LP-WAN candidates to flourish enough to come up with mature solutions. Almost all the LP-WAN solutions are well capable to address the most critical issues like cost, coverage, current, and capacity of these networks. They can be seen in two different categories; Proprietary and standard LP-WAN solutions.

Both of them have their own pros and cons. The standard LP-WAN solutions do not require a new infrastructure from the scratch, instead, what they only need is a software update to the existing infrastructure. On the top of it, they are very much available in almost all the countries with almost 100% area already covered by multiple operators in each country and they are very much capable to provide services not only locally but beyond the borders by reaching out different roaming agreements.

On the other hand, proprietary solutions have to undergo deployment from the scratch though faster enough because of their operation in unlicensed Industrial, Scientific, and Medical (ISM) spectrum. They do not suffer from interference and resilient enough towards multi-path fading due to employing asynchronous communication protocols. However, they can offer limited Quality of Service (QoS), scalability and global reach as compared to standard solutions. When comes to cost and energy consumption, they are good enough in the sense that they neither need a separate subscription to start providing services nor they cause fast battery drainage to make the lifetime as longer as possible.

With this enormous growth in the years to come, the challenges faced by LP-WAN paradigm are also gigantic. One of the premier among them is energy utilization and, consequently, battery life belonging to these low cost modules. Although low energy consumption is one of the peculiarities of these networks, but energy exhaustive operation can still leave a serious dent on the hype of LP-WAN. As the radio modules belonging to almost all the technologies come with tiny battery offering a small amount of storage capabilities due to their size limitations, thus they are designed to support most optimized operation to prolong the battery lives as maximum as possible.

Such energy limitations might declare LP-WAN candidates unfit for several IoT use-cases which demand for the performance optimization (e.g., delay-critical applications). As performance optimization requires higher resources and it is not possible to achieve energy and performance optimization at the same time being two different objectives. Then, there are several energy exhaustive IoT use-case who require a relatively higher message frequency causing the motes depleting their batteries too earlier than their expectancy life of 8-10 years. On the top of it, it is generally undesired to replenish the batteries of these low cost modules because of their replacement cost (including higher labor cost needed to replace the batteries installed on harsh environment).

Hence, it is utmost important to investigate the energy harvesting potential in the realm of LP-WAN to arrange for a separate but parallel source of energy to make them suitable for a wide variety of IoT use-cases and to enable them turning themselves from energy optimized operation to performance optimized operation wherever needed. There is a wide range of energy harvesting techniques (including solar, wind, vibrational, thermoelectric, RF energy, to name a few) with their own pros and cons, with some of them to fit well in the LP-WAN paradigm.

To this end, we started off with reviewing the energy harvesting MAC protocols already available in the literature for low powered sensor nodes. The MAC operation also plays an important part as it is responsible for all the channel sensing, reception and transmission operation. Thus, it is important to understand the interplay between energy harvesting techniques and the MAC protocols towards achieving the joint performance optimization. A variety of energy harvesting MAC protocols are studied with a special focus on the fundamental techniques, evaluation approaches, and key performance indicators along with presenting the pros and cons of each protocol discussed which provides an insight of the various research challenges and design guidelines for the research community working in this area.

Moreover, the feasibility of a completely cable-less IoT deployments is investigated where dual radio LoRaWAN gateways are equipped with wireless backhaul and fed by a photovoltaic plant. To accomplish this purpose, the power demands of a dual radio gateway, that serves a mix of M2M applications and leverages different combinations of front-end chipset and backhaul wireless technologies, are evaluated. Then, the photovoltaic plants are properly sized in lined with those requirements and, installation as well as operational costs of this kind of deployments are properly calculated. Finally cost and carbon footprint savings analysis is presented to demonstrate the economic viability and environment friendliness for this kind of approaches to demonstrate its benefits for Mobile Network Operators (MNOs).

Furthermore, another most energy exhaustive use-case i.e., industrial monitoring is investigated employing LoRa monitoring nodes in the industry 4.0. Although duty-cycled operation can play its role to prolong the battery life of LoRa modules employed in a smart industry, however, it would introduce long communication delays causing a bulk of damaged products (i.e., higher damage penalty) on the production line in case of an anomaly. In an attempt to reduce damage penalty, battery replacement cost tends to go higher due to higher communication frequency (i.e., short sensing interval). The work presents a model to analyze this cost trade-off. We first analyze LoRaWAN performance in plain industrial environment and then highlight the benefits of energy harvesting potential available within an industry 4.0 in terms of prolonging the battery life of LoRa monitoring nodes and the flexibility of shortening the sensing interval as per the application requirement.

Moreover, some other correlated research activities, strictly in lined with those aforementioned, have been carried out during the PhD work. A list of produced scientific contributions is presented immediately following this introduction. To conclude, a brief description on the structuring of this dissertation is outlined below:

- Chapter 1: *Low Power Wide Area Networks and Technologies for future Internet of Things*. It discusses the motivation, main features, and recent challenges of the upcoming IoT technology, with a particular focus on the LP-WAN, their space within the IoT paradigm, some critical dimensions, design considerations, broad domains of prospective use-case, and the variety of real hardware products specifically designed for such applications. Finally LoRaWAN, one of the candidates among LP-WAN, technology is discussed in details with highlighting the significance of energy harvesting techniques in this domain.

- Chapter 2: *Energy Harvesting MAC Protocols for Sensor Nodes: Challenges and Trade-offs*. It starts with analyzing various energy harvesting techniques with their power densities, motivations for separate energy harvesting mac protocols, and provides an extensive list of energy harvesting MAC protocols available in the literature for a variety of use-cases in sensor networks. It finally outlines various research challenges, lessons learned and future research directions of this domain.

- Chapter 3: *A Feasibility Analysis on Cable-less Deployments fed by Renewable Energy.* In this chapter, to analyze the feasibility of fully cable-less LoRaWAN deployments, the energy demands for a dual radio gateway is evaluated so size the photovoltaic plant that can independently feed this type of deployments. It further evaluates the installation and operating costs for this kind of deployments and highlights the benefits of this system for the network operators.

- Chapter 4: *Energy harvesting LoRaWAN in the Industry 4.0; Cost Efficiency Optimization for Industrial Automation.* This chapter focuses on LoRaWAN deployments in energy exhaustive industrial monitoring use-cases and presents a model to highlight an interest cost trade-off (i.e., battery replacement cost vs damage penalty). It first evaluates LoRaWAN performance in an industrial scenarios and then investigates the advantages of energy harvesting potential available in industrial environment in terms of prolonging the battery life of LoRa motes in comparison with transmitting more frequently.

- Chapter 5: *Conclusions and Future Research Directions*: The chapter starts with the concluding remarks on this PhD thesis outlining the key findings of the overall work. It then highlights some cutting edge research directions to be pursued in near future.

Personal Scientific Contributions

Scientific contributions leading to publications during this PhD work are enlisted in what follows. They have been accepted for publication in international journals and in national events.

International Journals

1. Hafiz Husnain Raza Sherazi, Luigi Alfredo Grieco, and Gennaro Boggia," A Comprehensive Review on Energy Harvesting MAC protocols in WSNs: Challenges and Tradeoffs," Ad Hoc Networks, vol. 71, pp. 117 - 134, 2018. doi: 10.1016/j.adhoc.2018.01.004.

2. Hafiz Husnain Raza Sherazi, G. Piro, L. A. Grieco and G. Boggia, "When Renewable Energy Meets LoRa: A Feasibility Analysis on Cable-less Deployments," in IEEE Internet of Things Journal, May 2018. doi: 10.1109/JIOT.2018.2839359.

3. Hafiz Husnain Raza Sherazi, Muhammad Ali Imran, Gennaro Boggia, and Luigi Alfredo Grieco," Energy Harvesting in LoRaWAN: A Cost Analysis for the Industry 4.0", IEEE Communications Letters, Aug 2018. doi: 10.1109/LCOMM.2018.2869404

National Conferences

1. Hafiz Husnain Raza Sherazi, Luigi Alfredo Grieco, and Gennaro Boggia, Designing Energy Harvesting-Low Power Wide Area Networks, presented in the Annual Workshop of GTTI (Gruppo nazionale Telecomunicazioni e Tecnologie dell'Informazione), Bari (Italy), 25-27 Jun., 2018. (Best Paper Award).

1

Low Power Wide Area Networks and Technologies for future Internet of Things

This chapter starts with the brief introduction of the Internet of Things (IoT) paradigm and throws light on the Low Power-Wide Area Network (LP-WAN) technologies along with the wide set of application domains that will benefit from its integration and development. The most important emerging standardized protocol stack for this technology is described in detail, along with the relationship of included protocols with state of the art approaches. A high-level view of commercial hardware and software products, running and implementing the described protocol stack and already available on the market, is also provided.

1.1 Internet of Things; An Overview

The IoT [1]-[3] can generally be seen as a networked system of smart interconnecting objects (i.e., sensors, actuators, machines, vehicles, smart phones, and tablets etc.)[4]. These devices are capable to sense different types of data (i.e., temperature, pressure, light, acceleration, and so on) from the environment and, simultaneously, process it in real-time in order to react to some particular events.

The anticipated benefits gained by the rise of the IoT are significant in terms of economic impact and improvement of the quality of life [5]. As per some recent statistics forecasted by some induastrial giants [6]-[8], around 50 billions connecting devices are expected by 2020 as a part of IoT, more than 6 times the world's population, as depicted in Figure 1.1. According to an estimate, the total number of IoT devices in use, have reached 8.4 billion in 2017, a 31% increase as compared to 2016.

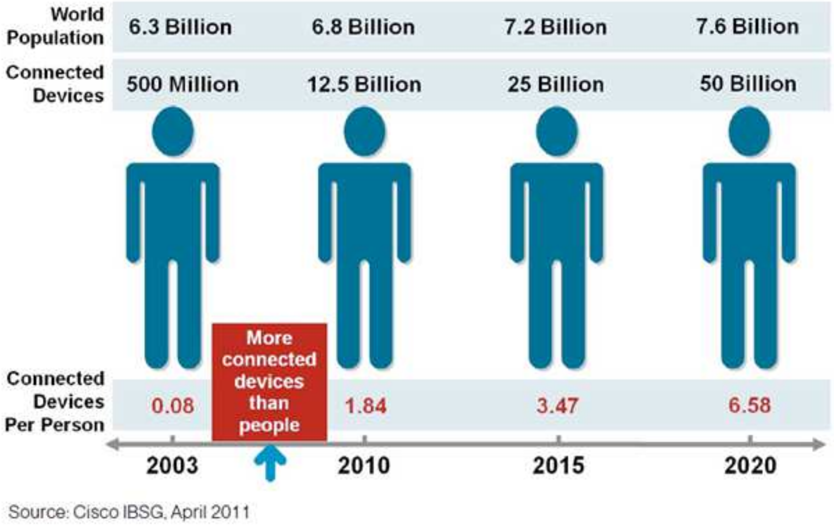
On the other hand, Intel projected the penetration of internet-enabled devices to grow from 2 billion in 2006 to 200 billion by 2020[1], that implies nearly 26 smart devices for each human on Earth. As per another estimation[1], the number of connected devices will be 75.4 billion in 2025 and 125 billion by 2030. Some companies have presented their numbers, taking smartphones, tablets, and computers out of the equation. Gartner estimated, 20.8 billion connected things will be in use by 2020. Similarly, IDC estimated this number as 28.1 billion and BI Intelligence at 24 billion. Gartner also gave an estimate about the total spend on IoT devices and services at nearly $2 trillion in 2017, with IDC projecting spending to reach $772.5 billion in 2018, 14.6% more than the $674 billion it estimated to be spent in 2017, with it hitting $1 trillion in 2020 and $1.1 trillion in 2021[1].

This uncontrollable explosion of smart devices will pave the way towards ubiquitous services in different application domains(i.e., health care, smart city, energy management, military, environmental monitoring, and industry-automation, to name a few [9]). Moreover, it further motivates the current efforts by the research community, industries, and standardization bodies worldwide, devoted to solve a plethora of issues still opened in this ebullient context [9]-[11]. The smart objects forming and enabling the IoT are generally resource constrained(i.e., limited computational, storage, and communication capabilities). They usually communicate over loosely-coupled short-range low-power wireless links up to a centralized storage and computational element, able to provide coordination capabilities for the entire network.

Right after their inception back in 1999 [12], IoT started attracting a lot of attention not only from industry but also from academia. During the last decade, its meaning and scope has undergone a lot of modifications and adjustments, from Wireless Sensor Networks (WSNs) to Industrial IoT (IIoT). The current trend is evolving toward the concept of the Internet of Everything (IoE), i.e., the intelligent connection of people, processes, data, and things. The vision of the IoE describes a world where billions of objects are enriched with sensors capable to detect, measure, and assess their status

---

[1] IoT Devices:https://internetofthingsagenda.techtarget.com/definition/IoT-device



Source: Cisco IBSG, April 2011

Figure 1.1: Evolution of number of IoT devices and world population in the last decade

in real-time. All such solutions use devices connected over public or private networks using standard and proprietary protocols. It is worth mentioning that IoE is built on the top of the IoT, employing the things in a wider fashion, with improved connections between people, data, and processes. It further enhances the power of the IoT, with expanded business opportunities and industrial outcomes. Until now, a plenty of different technological frameworks have been proposed to cater the very requirements imposed by IoT that have been derived out by looking at the main obstacles faced by IoT in the present era.

As discussed earlier, where exponentially increasing demand of IoT infrastructure has given birth to enormous opportunities, it simultaneously invites several challenges as shown in Figure 1.2 . Some of the main challenges [13] that hindered the development of IoT and lead to the need for LP-WAN paradigm, are the following:

1.1.1 Interoperability

Assuring the interoperability of the IoT devices made by different manufacturers is one of the premier challenge of IoT concept. In the presence of various communication channels and a wide range of IoT applications, a single communication protocol is never a viable choice. Hence, the interconnectivity of huge data with different data formats on a worldwide scale appeared to be one of the goals of IoT.

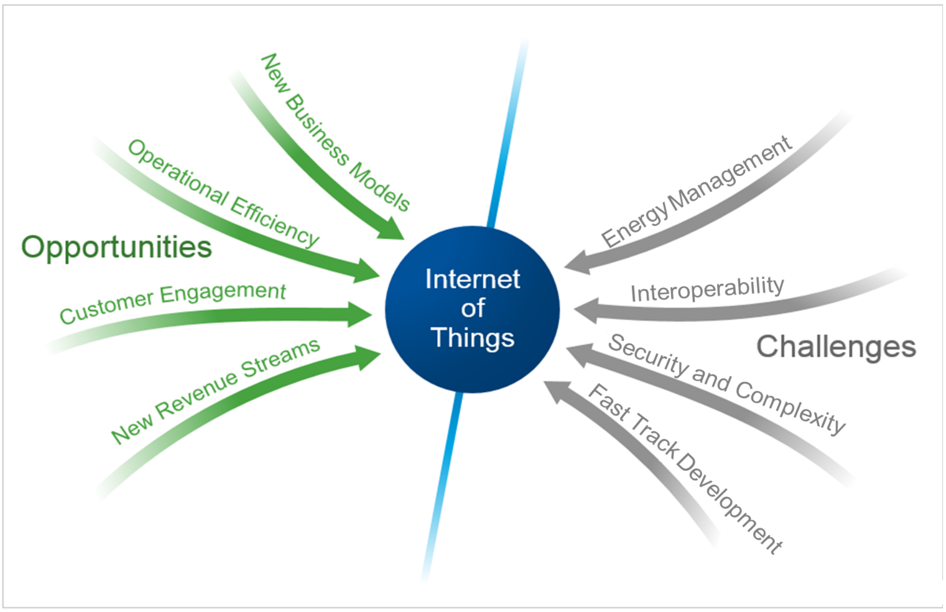


Figure 1.2: Oppurtunities and Challenges for IoT systems

1.1.2 Energy Management

As most of the modules are battery powered in nature, so it is equally important to reduce the energy consumption of these modules. Since these are the low cost modules, so battery replenishment can not be a suitable approach because this operation could be more expensive to the administration as compared to replacing the whole module. Hence, the battery life span of this kind of module should be up to several years. This requirement instigates the need for the energy efficient communication strategies to cope this challenge. A more recent solution to this kind of issues is the improvement of several energy harvesting mechanisms. The discussion on this kind of techniques follows in the Chapter 2 and a feasibility of different strategies for a plethora of LP-WAN use-cases is investigated throughout this dissertation.

1.1.3 Fast-track Development

The power of IoT keeps wrapping around the universe on an extra ordinary speed and hundred or thousands of such IoT objects are being the part of this system with every passing day. There are several issues that have already been arisen with this rapid growth and increase in the application complexities, and there may still be a bulk of issues and deployment difficulties yet to be explored in coming future. The vision of IoT concept is constantly and rapidly changing and there is a need of time to explore the new technological wave to have an eye and run aside this rapid development.

1.1.4 Security

As we have discussed earlier, IoT wave is moving so fast. Where this rapid development provides a foundation to revolutionized our lives, there are always the security threats that are penetrating with the same velocity. If we do not take these treats seriously, we are going to put our lives on stake for an unbearable loss. Therefore, a lot of work needs to be done on security aspects to take a dive on this ocean with better provision of security levels and roles of each of the entities. Developing new encryption and authentication protocols are inevitable for all the IoT applications keeping in view the limited resources available for a smooth operation.

1.1.5 Technological Complexity

Just like any other giant system, IoT faces several complexities to go through the final deployment process. These complexities are not only related to designing, building, and testing of the IoT hardware and software but it also includes infrastructure setup, domain expertise, scalability/flexibility of the system [14], and networking complexities as well. Then, there may be a fair level of complexity involved in the security and privacy maintenance. A lot of research is being done on this kind of complex issues and people are looking on the new ways toward efficient integration of the communication capabilities.

1.2 Low Power-Wide Area Networks for IoT

The LP-WAN [15, 16] is one of the few families came out to serve the dense IoT networks. The LP-WAN paradigm can be seen as the key enabler to affordable, efficient, and globally available IoT infrastructures. The LP-WAN employs existing radio networks to connect end-points located far away from one another and that's too with affordable cost and very low power consumption. The transmissions employing LP-WAN can be seen as many folds cheaper than that of cellular networks(e.g., General Packet

Radio Services (GPRS), 3rd Generation (3G) systems). A fairly high receiver sensitivity achievable through LP-WAN, permits achieving longer coverage up to several kilometers even with the lowest output power consumption. On the top of it, the types of Integrated Circuits (ICs) used in this kind of networks are not so expensive (i.e., up to only a few euros [17]).

All the challenges discussed in Section 1.1, were being taken care of under the umbrella of the IoT concept until 2014. Then, the LP-WAN were emerged for M2M low bit-rate communication with least cost and power requirements, than a conventional mobile network, to target a longer coverage areas. This kind of technological shift was inevitable for battery powered sensors, actuators, and microprocessors to operate efficiently and effectively in a resource-constrained environment like IoT. LP-WAN are designed with the intention to ensure smooth operation of these IoT devices for a longer period over single-hop long range communication links among a bulk of IoT devices.

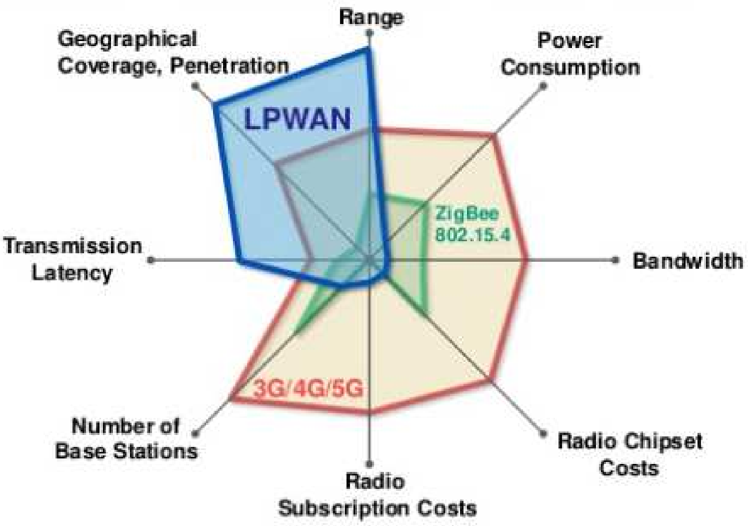


Figure 1.3: Dimensions that make LP-WAN special in comparison to other technological options

The following are some of the critical dimensions [18] demonstrating the need for LP-WAN as shown in Figure 1.3. These and common characteristics differentiate LP-WAN with already existing wireless technologies actively considered until 2014.

1.2.1 Range

The range is one of the few dimensions that can be seen as critical for LP-WAN as the core purpose of this kind of networks was to target widespread geographical areas on very low cost if we need to rarely transmit only a small amount of data. Although, the conventional cellular networks (4G/LTE) are well capable to cover wide geographical areas but their Operational Expenditure (OPEX), Capital Expenditure (CAPEX), and power requirements are so high that makes them unsustainable for IoT networks.

1.2.2 Power Consumption

Another most significant dimension that differentiates the need for LP-WAN is the power consumption. As most of the IoT modules are battery-operated and are intended to live for a longer period of time hence, it was important to have a technology (like, LP-WAN) where the radio units require minimal output power even when achieving higher receiver sensitivity.

1.2.3 Bandwidth

There are a bulk of low data rate application use-cases for IoT whose bit-rate requirements are very low. The primary goal for this kind of applications is to support smart decision making based on the received data (i.e., only a few bits) by several sensor deployments.

1.2.4 Radio Chipset Costs

This is another significant factor that makes LP-WAN more promising in comparison to other existing approaches. As discussed earlier, there is an enormous increase in the IoT devices with every passing moment so it could have been impossible for this IoT concept to move with such a rapid pace if the module costs would be higher. The costs of this kind of radio modules are usually very low (e.g., LoRa module starting from as low as €2.65[1]) when compared to $Zigbee^{TM}$ or Global System for Mobile (GSM).

---

[1] LoRa Module Price:`https://www.ebay.it/itm/433M-Lora-Ra-02-Long-Distance-RF-Wireless-Module-SX1278-123175834726`

1.2.5 Radio Subscription Costs

As most of the existing candidates under LP-WAN paradigm operate in unlicensed band of the spectrum under 1 sub-Ghz and they do not need heavy subscriptions on annual basis, so they are the most promising options that can fulfill the most of the IoT application requirements even obeying the local duty-cycle regulations in sub-GHz band.

1.2.6 Number of Base Stations

Exploiting the advantage of long radio coverage, fewer number of base stations are required to cover huge areas. As LP-WAN base stations are well capable to cover up to thousands of end-devices in a single LPWAN cell hence, the total number of base stations required could be even lower than IEEE 802.15.4 as shown in Figure 1.3.

1.2.7 Transmission Latency

Transmission latency could be seen as the only downside of this kind of networks due to limited bandwidth and local duty cycle regulations that may limit the throughout and cause longer delays. Nevertheless, it is still a fairly good trade-off when you have a very low-bit rate requirements with a frequency of few message per day in a bulk of non real-time applications where a delay up to several seconds can be tolerated.

1.2.8 Geographical Coverage

Achieving longer radio coverage, of up to 5 kilometers in dense urban environment and up to less than 15 kilometers in a countryside, is one of the common characteristics present in LP-WAN family. As most of the LP-WAN candidates are characterized by reasonably higher Maximum Coupling Loss (MCL), hence they are well capable to achieve a receiver sensitivity of up to -137 dB. The higher the MCL value, the more robust the link would be, belonging an LP-WAN network.

1.3 The evolution of Low Power Wide Area Networks

The LP-WAN family precedes a very interesting history as shown in Figure 1.4 and discussed throughout this section.

The AlarmNET [19] was introduced by Alarm Device Manufacturing Company (ADEMCO), one of the pioneer alarm manufacturer later acquired by Honeywell, in early 90s that could be seen as an analogous to LP-WAN as it was designed for a very small amount of data on 928 mHz band. This network operated in 18 major areas across the US and covered approx. 65% of the urban population at that time.

ARDIS [20], another wireless wide area technology owned by Motorola, was previously introduced in 80s with the intention to fulfill the need for lower bit-rate applications. Even though, it was relatively a slower network but have been used in a number of applications like sales automation, fleet tracking, and e-mail to name a few[1].

Figure 1.4: History of Low Power Wide Area Technologies

In a few course of time, cellular mobile operators realized this fact that they need to support small data and voice, and 2G came into the market in late 90s. As soon as it became available to the public after a successful testing phase, most of the similar companies in alarm manufacturing and from several other lines migrated to the cellular technology because of the readily available deployments and the lower cost of the modules because of increased production volume with time.

Then, a plethora of wireless technologies came into play to serve a fair portion of applications with different needs. There are several options for short range communi-

---

[1] `https://www.iotforall.com/history-of-lpwan-look-future-of-lpwan`

cation and a range of standards (such as, Radio Frequency Identification (RFID) [21], Near Feild Communication (NFC) [22], Bluetooth [23], Bluetooth Low Energy (BLE) [24], and Zigbee^{TM} [25]) were introduced to target a small subset of use-cases for each.

For example, RFID has been used to track inventory and for supply chain management. The passive tags on a range of products contain product information that can be read via special handheld readers within a distance of 100m supporting a unidirectional communication. Similarly, NFC can also read/write tags but , unlike RFID, these tags can be employed in an unlimited number of products due to their simple design and any regular NFC-enabled device can read their information. The NFC also supports bi-directional communication and, according to an estimate[1], it has been used in over a billion devices so far.

The Bluetooth standard was another game changing invention in mid 90s facilitating the connectivity of a huge number of handheld peripherals with personal computers. They have been a hot choice for a variety of devices to establish short range (often in the range of $10m$) connections with each other and they were assumed to support relatively a higher data rate than the predecessors. Bluetooth could support the pairing of up to 8 devices on the cost of higher energy consumptions in comparison to other candidates where each pairing device is an independent component.

The Zigbee standard, conceived by Zigbee Alliance in 2005, was another success story in the series of short range technologies. It offered to optimize communication range with lowering down the energy consumption significantly as compared to Bluetooth. Zigbee devices could support a radio coverage of up to $100m$ with the provision of relatively higher data transfer rates.

Soon after the appearance of Zigbee, Bluetooth special interest group started worked in the same dimensions to overcome the energy issues of Bluetooth technology and, just an year after the inception of Zigbee in 2006, they were able to introduce BLE aiming to reduce the energy consumptions by putting the connections on sleep mode once inactivity is detected for a any time span.

Wi-Fi [26] is another success story, owned and maintained by Wi-Fi Alliance, which was introduced as a part of WLAN following 802.11x family of standards. Wi-Fi can be seen as the most famous and widely used option so far which is great for providing high speed connectivity (e.g, watching a movie online and downloading a video game)

---

[1] `https://nfc-forum.org/nfc-bluetooth-and-rfid-unraveling-the-wireless-connections/`

for home and office users (i.e., local area) while bearing a relatively lower cost (i.e., as monthly subscription fee or modem charges). The only downside is the relatively higher power consumptions and the provision of this connectivity for a very short vicinity and the signals might face severe attenuation where the distances are involved between an Access Point (AP) and the end-user. Several follow up versions of 802.11x family have continuously been introduced so far, overcoming a plenty of issues related to the performance of Wi-Fi.

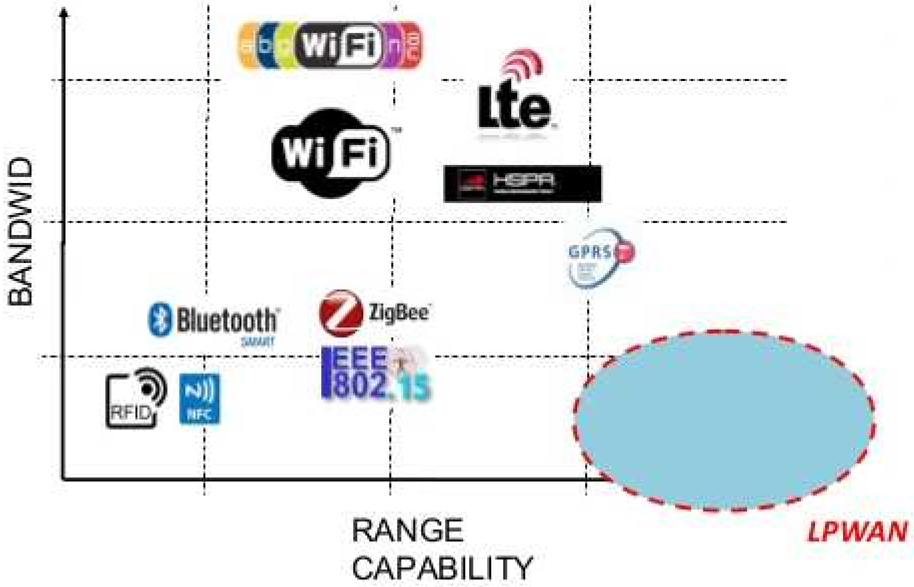


Figure 1.5: Motivation for LP-WAN compared to different wireless technologies with radio coverage and bandwidth perspective

The cellular standardization bodies have never been behind, realizing the technological transformation and the continuous work was going on building the new cellular standards for each type of communication (i.e., M2H or M2M). To cope with the increasing demand of data and voice services, MNOs have already traveled across the way from GPRS [27] to LTE-Advanced [28] high speed services. A variety of new standards (such as, Nerrow Band-Internet of Things (NB-IoT) [29], Extended Coverage-GSM-IoT (EC-GSM-IoT) [30], and Long Term Evolution-Machine Type Communication (LTE-MTC) [31]) have been introduced by 3rd Generation Partnership Project (3GPP) anticipating the need for M2M communication to compete with open LP-WAN standards. Among them, NB-IoT was the one with more popularity and is well on its way to compete several LP-WAN options introduced by open Alliances (i.e., LoRa and Sigfox) in the recent past.

At one hand, where local area technologies (as shown in Figure 1.5 and discussed throughout this section) are able to well serve different mobile use-cases with short range requirements, they do not fit well for many energy-critical applications demanding long radio coverage [32]. On the other hand, cellular standards are good to cover long geographical areas with higher data rate connectivity, they declared unfit for a bulk of IoT use-cases because of a huge number of tiny devices that solely rely on their batteries for communication and frequent battery replenishments are not possible.

The cost factor is the second, instigating the need for LP-WAN technologies as the conventional cellular modules are not affordable when it comes to dense IoT networks. As the IoT modules belonging to LP-WAN family are considered simple and lightweight devices costing only a few euros [17] and are well capable to survive for a longer period of time (up to ten years) hence, they are being considered the future of IoT concept and MNOs are putting the full of their attentions and they are ready for different public and private network partnerships to provide cheaper low-rate services on longer distances(i.e., remote areas) as shown in 1.5.

1.4 Prospective applications of Low Power-Wide Area Networks

The LP-WAN are successfully targeting a pile of IoT use-cases that would briefly be discussed throughout this section.

1.4.1 Smart Home

The smart home applications [33] are the pioneers to be covered by most of the LP-WAN solutions as they were the major source of motivations for such a technological transformation into an IoT era. Some of major applications in this area are the following.

- **Home Security:** Home security applications ensure to safeguard smart homes from burglary, theft and unauthorized entrance. This kind of applications take control of the security through intercoms, security cameras, doors, window alarm sensors, and automatic door locks that can be used strategically. It allows the applications to secure the vicinity against potential threats. The entire security system can be operated from anywhere by key chain sensors and smartphones.

- **Smart Metering:** Smart metering is one of the popular use-cases of smart homes as it not only provides the ease to take readings remotely instead of arranging regular visits to utility holder but it also offers accuracy and speed as compared to conventional ways of meter readings. On the top of it, it facilitates customers to have a better control over their usage and they can anytime check and pay their bills with just a few clicks/taps from the comfort of their homes.

- **Smoke Detection:** Smoke detection systems are one of the useful utilities and an integral part of today's smart homes. These systems are now available in almost all the newly-built residential and official buildings to detect any kind of smoke caused when it goes beyond a certain threshold. This kind of applications have smoke sensors connected to the system and the micro-controllers issue instructions to make alarms unless the smoke level goes down.

- **Fire Alarm:** Just like smoke detectors, fire alarms are also a part and parcel for smart homes. Fire sensors are deployed across the building structures which continuously sense the environment for the presence of fire and immediately inform the micro-controllers to generate alerts in the case of emergency. This kind of systems automatically call the corresponding helpline of the fire brigade systems to timely control the damage.

- **Indoor Air Quality:** Indoor air quality is one of the key measures for maintaining the expected health grades of inhabitants. In the presence of a variety of appliances and devices releasing toxic gases, it becomes even more challenging to maintain a healthy environment for human-beings. This kind of systems not only monitor the rate of this kind of polluted gases within the environment but they also take corrective and preventive measures when needed.

- **Smart Appliances:** There is no concept of the smart homes if there would not be the presence of the smart appliances. For example, the refrigerator available in a smart home not only maintains the refrigeration temperature according to the outside whether but it also keeps track of the inventory of eggs and is fully capable to make a list of shopping items missing or nearly finishing goods from the fridge.

1.4.2 Smart City

Similarly, the smart city applications [34]-[37] are no exceptions and have attracted the attention of most of the city councils in developed countries. They are being targeted by most of the technologies recently appeared under the umbrella of LP-WAN. Some of the major candidates are discussed as follows.

- **Smart Street Lighting:** Smart street lighting is a tremendous concept being adapted in the developed cities. This kind of street lights are more intelligent as compared to conventional street lights as they are capable to detect the movement of pedestrian, cyclists, and traffic on a road and changes its behavior accordingly. Instead of dimming themselves on regular intervals, they are switched off when there is no movement around and switched on again whenever the sensors detect some activity. They are significant part of a smart city as they contribute to save a huge portion of electricity that would, otherwise, be going to waste in case of conventional street lights.

- **Environmental Monitoring:** The environmental monitoring systems have a broader spectrum of usage in a smart city. They keep track of almost everything right from the level of ozone in a meat packing facility to the smoke monitoring in the national forests. These are also responsible for monitoring a lot of toxic gases present in the environment from carbon contents to smog-like gases, from thermal contaminant to chemical leakages present in the water, from monitoring moisture to vibration level of soil, from earthquakes to tsunami warnings to avoid natural disasters[1].

- **Smart Waste Management:** Smart waste management systems are also a building block of a smart city and they are mainly aimed at achieving two different objectives. First, reducing the amount of time and energy required with an efficient waste management solution. Second, reducing the amount of waste

---

[1] Environmental monitoring use-cases: `https://www.link-labs.com/blog/iot-environmental-monitoring`

produced by employing several smart strategies. By spending the small upfront costs, municipalities can significantly cut down their operational costs in addition to operational efficiency.

- **Smart city Parking:** Smart city parking offers an innovative solution to a burning issue of finding parking slots in smart cities. The real time parking maps can be generated employing the integrated data collected through a bulk of sensors deployed on the grounds, mounted in the cameras, and installed on the light poles on different places within a smart city. This map is continuously updated by the provision of latest data and is broadcasted to the drivers to spot out a nearby slot without being panic to avoid anxiety. It not only saves on fuel for the drivers but also reduces the traffic burden on the main routes during peak time slots.

1.4.3 Smart Industry

This class of services is utmost important and the major beneficiary of LP-WAN technologies [38]- [41]. This wave of smart services is a backbone for economic development of an industry and has made it possible the transformation into the fourth industrial revolution.

- **Water and Gas Leakage Detection:** Among many others, leakage detection has been a very common problem especially in oil and gas industry. According to an estimate, an advanced level sensor deployment across the industry and effective pipeline management can result in saving around $18 millions[1] which, straight away, adds to industrial revenue. The implementation of IoT concept in industry 4.0 not only enables higher management to make smart decisions on the real-time information at hand but reduces equipment failure, increases the safety levels, and can significantly reduce the downtime in a smart industry that eventually leads to higher production efficiency.
- **Pollution Monitoring:** The core purpose behind establishing this kind of systems is to keep an eye on the industrial environment that have higher tendency

---

[1] `https://dzone.com/articles/iot-enabled-leakage-detection-system`

of being pollutant due to a number of factors like closed environment, heavy machinery, higher emission of carbon footprints and many others. Different types of sensors deployed in a smart pollution monitoring systems continuously take readings and generate appropriate alerts wherever needed without any human interference to ensure a safe environment for the workers working in those industries.

- **Predictive Maintenance:** Maintenance is really a cumbersome task and it is important to ensure machine availability to optimize resource utilization while maintaining the quality of the product. Thanks to the inherent capabilities of industry 4.0, predictive maintenance has never been that easy in the past. Through continuous collection of sensors data deployed across the production line, it is easier to evaluate the present condition of the equipment. As soon as an anomaly is detected by the system, it automatically generates alerts to take preventive measures on time to avoid huge financial losses due to the production of plenty of damaged products.

- **Temperature Monitoring:** Temperature monitoring systems are the key elements for some smart industries (such as, automotive, plastic and life sciences industries) where the whole industrial process solely depends upon the temperature of the production process. For example, Alloy melting quality in the automotive industry clearly depends upon the maintained temperature where even a small amount of variation in the temperature could ruin the finishing product. The temperature sensors take readings after regular intervals and the system generates appropriate alerts in case of variation in the required level of temperature that needs to be maintained. This timely information is fed to the expert systems in a smart industry to take timely decisions(e.g., stopping the production process) without delay to avoid further losses.

- **Tank Flow Monitoring:** Industrial tank level/flow monitoring is associated to several industries like fuel monitoring and liquid monitoring in the mining process. Monitoring can be inevitable for two basic reasons. First, to ensure the liquid from the tank does not run out entirely as it is needed with a certain ratio to propagate the normal processing of the plant. Second, the rate of flow of the liquid from the tank is in accordance with the expected usage of liquid in the next process. For this purpose, a hydrostatic sensor is normally used to gage the pressure between the water level and the upper surface of the tank and appropriate alerts are generated in case a problem is detected.

1.4.4 Precision Agriculture

The Information and Communication Technologies (ICT) in general, and IoT in particular, have revolutionized the way the agricultural activities were being carried out globally in the recent past [42, 43]. The precision agriculture market is expected to hit $2.42 Billion until 2020[1]. The LP-WAN are playing their role, like in any other field, to make the agriculture more efficient and productive at the same time. As per the statistics of World Bank[2], almost 80% of the agricultural consumption is produced by developing counties and most of the formers in those regions base their decisions on the guesswork and experience instead of any scientific guidance which can not be reliable for predicting some critical variables (such as, the water quality, soil conditions and so on.). Hence, by using precision agriculture, the production can be increased by many folds in comparison of what we get today [44, 45].

- **Smart Irrigation:** Smart irrigation is the key to precision agriculture. As water is the most significant resource on earth that is being reduced rapidly in different parts of the world. These systems are build with a single intention to save the water wastage. The sensors deployed across the field monitor the moisture level and the weather conditions to take accurate decisions ensuring the water motors/pumps are started only when they are inevitable.

- **Precision Farming:** Precision farming would change the way the farming is carried out conventionally as it enables the farmers to monitor and control their irrigation equipments, manage their farms in terms of efficient resource utilization like seeds, fertilizers, and water, and the current farm conditions can be monitored in real time. It would not only help the farmers to detect inconsistencies, but to reduce operational challenges being more cost effective. The precision farming

---

[1] A Forbes Report: https://www.forbes.com/sites/jenniferhicks/2018/04/30/why-precision-agriculture-will-change-how-food-is-produced

[2] Smart Farming and Precision Agriculture:https://www.arcweb.com/blog/iot-steps-smart-farming-precision-agriculture

employs technologies like sensors, actuators, Global Positioning System (GPS), Geographic Information Systems (GIS), and drones to measure spatial variability, communicate farm conditions, plan irrigation and harvesting, thus eliminating human intervention to a higher extent.

- **Smart Greenhouses:** : Thanks to the smart greenhouses, farmers can cultivate crops with no or minimal human intervention. Climatic conditions such as temperature, humidity, luminosity, and soil moisture are continuously monitored and maintained inside a greenhouse. Actuators can be instructed through triggers to take automated actions in case of variations in these conditions. Then, the changes would be evaluated based on these actions to implement corrective/preventive actions for the optimal condition maintenance of the plant growth.
- **Agricultural Drones Management:** : A variety of drones can be employed in multiple agricultural applications (i.e., monitoring of crop health, agricultural photography, and livestock management). Drones are able to scan a wide area at low cost and their operation can be integrated with different sensors to collect a variety of information at the comfort of farmer's home.
- **Precision Livestock Farming:** Precision livestock farming is able to support real-time monitoring of productions, health, and welfare of livestock to make sure that optimum yield is achieved. Advanced technologies let's the farmers to continuously monitor that facilitates them to take smart decisions to ensure improved animal health.

1.4.5 Smart Tracking

Where IoT serves to lift in a variety of domains, tracking options have also been reshaped according to new demands. Smart tracking [46, 47] is also one of the widely employed use-cases has become an integral part of the IoT concept. Thanks to the inception of LP-WAN, there are a range of smart tracking services being used these days and some of the important ones are outlined briefly.

- **Fleet Tracking:** Fleet tracking and management at construction sites is another widely applicable use-case. Plenty of fleets (e.g., tractors, trolleys, forklifts, and cranes) can be managed in a smart way and the costs,for putting them on site for more number of days they were actually needed, can be saved to increase the business revenue. A centralized surveillance is possible for all the fleets at work and their operation can closely be monitored to identify their repair cycles.

- **Asset Tracking:** This is one of the most famous use-cases of LP-WAN family where each asset is equipped with sensors and GPS system which is continuously in communication with the central site to have a real-time tracking of the asset giving the owner a provision to have a better control over his asset. Wherever and whenever he wants, he can be presented a real-time geolocation of his asset which avoids loss of valuable assets being stolen or theft.
- **Patient Tracking:** Patient tracking is one of the few noble achievements by IoT concept. Patients are always tracked to have a close eye on their critical condition. If something unfortunate happens to the patient, the system can generate the urgent alerts to the concerned persons including doctors so that they can they can be rescued whenever needed.
- **Logistics Tracking:** Logistics tracking is also an important need. The imported or exported goods used to take several months from source to destination and they tracking of goods in transit has never been an easy task. Thanks to the newly emerged wave of LP-WAN technologies, with smart tracking, the companies or individual can continuously track their goods while in transmit. At every single spot, from the airport to seaport, from harbors to warehouses, from godowns to containers, the logistics are absolutely traceable with the latest timestamps when they arrived on that spot. There is a growing interest in this area in the years to come.

1.4.6 Smart Healthcare

Smart healthcare [48, 49] is relatively a new area but a lot of work is being done to fully exploit the power of LP-WAN paradigm. Smart healthcare are mainly intended to connect all the stakeholders (i.e., doctors, caretakers, healthcare centers, emergency services) with an integrated platform to take care of the patients. There may be a plenty of different use-cases related to smart healthcare and only few of the important ones are presented below.

- **Medical Fridges:** Medical fridges or refrigerators are an essential part of the smart healthcare use-cases. This kind of medical fridges are capable of close monitoring on how a range of different vaccines are stored into this kind of refrigerator and how the transparent distribution of this vaccines or injections are made possible. This type of refrigerators can only be accessed by authorized personnels within a healthcare facility and they incorporate different computer vision and machine learning techniques to make this kind of systems behave more intelligently to serve with great accuracy.

- **Blood Pressure and Temperature monitoring:** This kind of auxiliary systems are useful to monitor several health care indicators remotely for the non-critical patients. Patients with the continuous problem of blood pressure can sometimes be in more serious situation but they can not be admitted indoor for a longer period of time to constantly occupy the hospital resources. In this situation, it is important to have an eye on their heath care indicators while letting them stay at their homes and when the readings go beyond a threshold, appropriate actions should be taken to inform all the parties involved.

- **Detection and reporting of emergency situations:** The smart healthcare facilities go a step ahead and are being used in detection and reporting of the causalities to the emergency control room. This kind of systems are fed with the latest abnormalities detected by the various types of sensors deployed across the field, fully integrated with the emergency control room to avoid the delays in case an emergency is detected. The emergency ambulances are instructed for immediate arrival of the causality spot by providing the coordinates transmitted through sensors to the control room.

- **Waiting time reduction in emergency:** The waiting times in the emergency is one of the hectic and tedious things to face. Prolonging this can of wait not only causes increased mortality but also effects patient's satisfaction level. Thanks to the usage of IoT, several hospitals have effectively reduce this waiting time up to 50% in United States[1]. Having partnership with GE healthcare, they have successfully deployed an IoT based software named 'AutoBed' which is able to

---

[1] IoT use-cases in Healthcare:`https://www.iotforall.com/exciting-iot-use-cases-in-healthcare`

track the occupancy among 1200 units and rates the emergency of a patient depending on several metrics to asses the emergency needs and generates alerts in case a patient needs urgent treatment.

- **Enhanced Drug Management:** Last but not the least, IoT has revolutionized the drug management systems not only for the patients but for the ease of healthcare professionals. With the invention of smart drugs, there are plenty of smart products available [1] (e.g., sensor-embedded pills, smart pill bottles, smart contact lenses and many others.) on the stores to enhance the healthcare experience. For example, healthcare professionals can prescribe a sensor-embedded pill, just like any other regular medicine, containing a small sensor of size of a rice grain. It enables them to get a better insight of the problems once swallowed. It can report a variety of issues like rest and activity patterns of the patient by communicating with the patch that was worn by the patient. Similarly, the smart pill bottle keeps monitoring when a pill is taken by the patient and it can generate a reminder if needed. The smart lenses to measure the glucose level from the blood are also in the market for diabetic patients.

1.5 Design Considerations for LP-WAN Technologies

After having a look on the possible LP-WAN applications in Section 1.4, it is now important to discuss several design considerations for this paradigm which are critical to consider for achieving various , sometimes contrasting, design objectives [50]. Few key design considerations of LP-WAN technologies are as follows.

1.5.1 Long Radio Coverage

Achieving radio coverage over a wide area is one of the core design considerations for LP-WAN technologies. These are designed to achieve up to +20 dB gain over conventional cellular systems which permits end-nodes belonging to LP-WAN connecting to the base stations on a distance from few kilometers (in urban area) to few tens of kilometers (in a countryside)[51]. This long radio coverage can be achieved exploiting two different techniques; choice of frequency band and modulation techniques[15].

---

[1] Smart Drugs: where IoT meets healthcare :`https://siliconangle.com/2015/06/30/smart-drugs-where-iot-meets-healthcare-a-market-snapshot/`

Most of the technologies under this paradigm operate on sub-1GHz frequency band for two reasons [51]. First, this portion of the spectrum yields reliable communication on low power budget which offers least multi-path fading and attenuation when penetrating through high roof buildings. Second, this portion of the spectrum is not very congested in comparison with 2.4 GHz which is used by most of the other wireless technologies like Wi-Fi. Similarly, most of the LP-WAN candidates employ narrow-band and spread spectrum modulation techniques which offers higher link budgets through encoding the signal into narrow bandwidth and less susceptible to interference being below the noise floor.

1.5.2 Low Bandwidth

Most of the technologies under LP-WAN, benefit from low bandwidth requirement as demanded by a variety of applications discussed above in Section 1.4. For example, Sigfox is known as an Ultra Nerrow Band (UNB) technology which employs as short as 100Hz width, thus increasing the number of end-nodes per unit bandwidth and further reducing the noise level [52]. LoRaWAN is adaptable in that it employs three different bandwidth options to select from, as 125 kHz, 250 kHz, and 500 kHz. Whilst NB-IoT offers a fixed short bandwidth of 180 kHz [15].

1.5.3 Low Bit-Rate

Low bit-rate relaxation serves as the main motivation to make possible the phenomenon of LP-WAN which enables them to be extremely low cost with the batteries lasting several years even offering a wide radio coverage. It also makes possible to design a simple LP-WAN radio module with least complexity and cost [53]. This is one of the core motivations that differentiate LP-WAN from legacy cellular systems. For example, the maximum bit rate LoRaWAN can support starting from 290bps to few thousand bit per second [54]. Similarly, the Sigfox nodes can achieve up tp 100bps while a bit rate of 250 kbps is achievable with NB-IoT.

1.5.4 Latency

The delay is another significant design consideration for LP-WAN technologies as the delay-tolerant use-cases (such as, smart metering) are the main target for this family.

As almost all the technologies belonging to this family are characterized by a significant delay in terms of seconds, thus declared unsuitable for delay-critical IoT applications [55]. The applications having low bit-rate demand and are insensitive to the latency can be better served by A-class end-nodes of LoRaWAN and Sigfox while delay-critical applications be better served by LoRaWAN C-class and NB-IoT on the cost of higher energy consumption [15].

1.5.5 Application Payload

Application payload is another important characteristic of LP-WAN technologies and most of them have a smaller payload size to support low bit-rate applications. NB-IoT offers the transmission of data up to 1600 bytes that is higher as compared to other proprietary technologies of this family. LoRa provides flexibility exploiting Adaptive Data Rate as it has different payload size for different configuration settings supportable by this standard. The minimum payload size of LoRa is 51 bytes with 13 bytes overhead of protocol header while the maximum payload size can reach up to 243 bytes depending upon the LoRa Spreading Factor (SF) (see Section 1.7.4 for detail on SF) [56]. On the other hand, Sigfox offers an application payload size of 12 byte at maximum that may prove to be a limitation for various IoT applications with higher data rate needs.

1.5.6 Topological Structure

Topological structure is an important consideration for a technological perspective as it decides how (in which fashion) the different network components shall combine with each other to form an architecture. The end-nodes in most of the LP-WAN technologies follow a star or a start of star topological structure [57]. This kind of topological structure helps to achieve other interrelated design objectives. For example, star-like structure is pretty simple to deploy that guarantees directly connectivity of end-nodes with the gateways that helps making it energy efficient and low cost by eliminating the need for the relays as in mesh network structure where the nodes would be utilizing their energy in relaying the communication of other nodes and due to the geographical location of certain nodes, the communication would needed to be routed through them most of the times. Consequently, they would get their batteries depleted earlier than the other nodes present in the system.

1.5.7 Uplink and downlink message frequency

Almost all the technologies under LP-WAN to date are capable to support only a limited number of messages on uplink and downlink being simple, low cost, low bit-rate, delay-tolerant, and under the strict duty-cycle regulations. Although uplink traffic is dominant in this kind of networks but, most of them still benefit from bidirectional communication but with lower privileges on the downlink. For example, Sigfox can support up to 140 messages of 12 $byte$ at the uplink and only 4 messages, of 8 byte each, per day on the downlink that is the maximum band occupancy limit imposed by European duty-cycle regulations for 863-870 MHz band of the spectrum [58]. Similarly, 1% of duty-cycle implies a maximum transmission time of 36 seconds/hour per end-node in LoRa [59].

1.5.8 Reliability

Reliability can be referred to as an important design consideration. As Sigfox and LoRa both operate in an unlicensed ISM spectrum employing asynchronous communication protocols and can be characterized by inter-channel interference and multi-path fading, and they may not guarantee the same QoS as compared to NB-IoT operated in a licensed spectrum [60]. NB-IoT employs LTE-based synchronous communication protocols which are, of course, optimal to ensure QoS but on the cast of being more expensive.

1.5.9 Security

Security is another important consideration for many IoT use-cases. Where the rapid IoT development provides a foundation to revolutionize our lives, there are always the security threats that are penetrating with the same velocity. If we do not take these treats seriously, we are going to put our lives on stake for an unbearable loss. Most of the LP-WAN candidates have a built-in security mechanism and the communication benefits from various end-to-end encryption strategies. For example, LoRa is protected by Advanced Encryption Standard (AES) 128-bit end-to-end encryption which provides an ample cover to secure the important data belonging to a range of LP-WAN applications [61]. The NB-IoT also benefits from Long Term Evolution (LTE) encryption fulfilling the demands of several use-cases and they are planning to come up with an end-to-end security mechanism like LoRa. Sigfox suffers in that it has not been considered much with respect to security but they are also onto it to overcome this issue soon.

1.5.10 Capacity

Almost all the technologies in this family are great towards capacity and scalability [14]. They are well capable to practically support thousands of end-nodes per gateway in a cell [54]. As these giant networks are meant to be highly dense with continuously increasing number of nodes, thus these networks benefit from several techniques to cope with this issue (e.g., smart channel utilization in time and space taking advantage of such a narrow bandwidth requirements by individual nodes and adaptive data rates).

1.5.11 Deployment Model

Although following the same business objective to get the maximum number of MNOs around the world, all these key players have their own deployment and business model. For example, Sigfox is a proprietary solution providers following the top-down approach in the sense that they own the entire network; from all the back-end data and cloud servers to end-node software but they are open with respect to the end-node's radio technology. They agree to share their radio technology to any silicon manufacturer provided that they agree to abide by their basic terms of services. A lot of manufacturers (e.g., Taxas Instruments, Atmel, STMicroelectronics, and many others) are already on their way making Sigfox end-nodes. Sigfox strongly believes that keeping the application cost low, is the key to drive business [62]. On the other hand, LoRa is an open alliance who claims to be more open than Sigfox because of their open specifications. Any vendor can make an end-node or gateway that conforms to the LoRa specifications but the only catch is, Semtech Inc. is essentially the only silicon company making their radio, thus even if the ecosystem itself is open, it has a closed element. The most positive thing about LoRaWAN is, it would not be driven by a particular company which really slows down the development. LoRa Alliance strongly believes on the slogan of "openness creates adoption" with the provision for the enterprises to set up their own private LoRa network in addition to public networks. Unlike both the proprietary solutions discussed above, NB-IoT entirely follows a different model. They are the favorable choice for those MNOs who are interested in the upgradation of their existing LTE networks to be tuned for M2M communication instead of deployment from the scratch.

1.5.12 Cost per unit

Looking at the deployment model above, it is clear that all the candidates in the realm of LP-WAN, believe that reducing the per unit cost of their module is a key to their successful business growth [62]. There are three main reasons to achieve this business objective for all the players in this area; 1) reduced hardware complexity, 2) minimal infrastructure cost, and 3) most of them operate on unlicensed ISM band (except NB-IoT) to further reduce the cost element.

1.5.13 Long Battery Life

Ultra low power operation is the key to LP-WAN phenomenon [15]. All these technologies in the area of LP-WAN employ various important techniques [15] to accomplish this objective. First, as discussed earlier, they employ a simple topological structure(such as, star type) to avoid the overheads incurred due to complex structure. The purpose is to provide all the end-nodes a direct connectivity instead of relaying their communication that induces several overheads in terms of surplus energy utilization in non-important tasks. Second, the nodes belonging to all of these technologies undergo duty-cycling techniques to maximize their energy consumption by limiting the amount of time the nodes spend in transmission. Third, All of them avoid employing complex MAC protocols which, consequently, cause the nodes to drain more rapidly in complex MAC operation. Instead, they prefer to use simple ALOHA type MAC schemes to prolong their battery life as maximum as possible. Indeed, employing this type of protocols cause relatively higher collision rate but their simplistic operation saves more energy as compared to complex protocols with least collisions. Fourth, the complexity of the end-nodes belonging to LP-WAN technologies was off-loaded to shift more operations on to the other components (such as, gateways and cloud/network server) of the architecture, thus enabling them to operate more optimally that surely adds time to their life.

1.6 Real LP-WAN based products available in the market

Soon after the emergence of LP-WAN concept floated over the surface, it has attracted a lot of companies plunging into this market to provide different components and services. Anticipating the technological transformation towards IoT era, silicon manufacturers have already started building a variety of gateways and end-devices conforming to the specifications of wide accepted LP-WAN candidates in this area. Some of the most widely adopted options are briefly outlined below among the gateways, as well as for the end-points.

1.6.1 Gateways

The gateway is one of the core components of LP-WAN family that relays the communication messages by the end-nodes onward to the network servers. There are a plethora of gateways, each with distinct characteristics, already available in the market to offer several IoT services for different LP-WAN and their suitability can be determined based on a range of features they offer [63].

1.6.1.1 Multitech Conduit

The Multitech Conduit is the most widely used LoRa-based gateway as shown in Figure 1.6[1]. It is a easily configurable, manageable, and scalable LoRa-based gateway and comes into a variety of versions with respect to supporting plug and play cards as demanded by the underlaying use-cases. It can serve a range of LP-WAN use-cases but, particularly, targets industrial IoT applications.

Figure 1.6: Multitech Conduit Gateway

---

[1] Multitech Conduit:`https://www.multitech.com/brands/multiconnect-conduit`

1.6.1.2 Embit EMB-GW1301-O

Embit EMB-GW1301-O is another upgradeable multi-services gateway as demonstrated in Figure 1.7[1] that is designed to cater M2M communication [18] for a range of IoT use-cases. It is also a LoRaWAN gateway to offer cost-effective solution that can simultaneously support communication on multiple channels. It employs advanced Semtech chipset SX1301, good enough to cover an area of 3 kilometers in urban and up to 15 kilometers in rural sides.

Figure 1.7: Embit EMB-GW1301-O Gateway

1.6.1.3 Kerlink Wirenet 868

Figure 1.8: Kerlink Wirenet 868 Gateway

It is one of the compact and light-casing LP-WAN gateway as shown in Figure 1.8[2]

---

[1] Embit EMB-GW1301:http://www.embit.eu/products/emb-gw1301gateway

[2] Kerlink Wirenet:https://www.kerlink.com/product/wirnet-station

that comes with ARM 926EJS processor and low power 128MB DDRAM and is well capable to listen 9 different LoRa channels at optimized power consumption and is able to offer a receiver sensitivity of -141 dBm and can exhibit a radio coverage of 15 kilometers in a sub-urban area. It is one of the favorite choice for the companies interested in setting up their own private networks in addition to support public networks.

1.6.1.4 LoRANK 8

LoRANK 8 is one of the affordable gateways available in the market (can be seen in Figure 1.9[1]) and is well capable to handle few ten thousands of end-devices in a single cell. It can also support communication on 8 different channels and can offer a receiver sensitivity of -138 dBm covering the most distant nodes in a cell. It comes with completely open hardware chipset (i.e., Beagle board) and customizable software, however, it comes with preloaded software from The Things Network[2] that can easily be operated without any prior technical skills required.

Figure 1.9: LoRANK 8 Gateway

1.6.1.5 Link-lab LL-BS-8

LL-BS-8 is an industrial grade gateway (in Figure 1.10[3]) to cater dense M2M traffic that comes with multiple data connections (such as, Wi-Fi, GSM, and Ethernet). It employs an active interference mitigation algorithm, and provides a long range and cost effective replacement choice for other wide area options. It is loaded with a powerful

---

[1] LoRANK 8:`https://www.ideetron.nl/lora/?lang=en`

[2] The Things Network:`https://www.thethingsnetwork.org`

[3] LL-BS-8 :`http://www1.futureelectronics.com/doc/LINK%20LABS/LL-BST-8.pdf`

CPU of AMD G Series with 2 GB of DRAM and 8 GB SSD storage. It can receive up to 8 channels simultaneously and capable to achieve a sensitivity up to -133 dBm.

Figure 1.10: Link-labs LL-BS-8 Gateway

1.6.1.6 Lorrier LR2

This professional grade gateway comes with durable metal case as shown in figure 1.11[1] that is more resistant to bad weather conditions because of IP66 protection. It supports Power over Ethernet (PoE) hence can operate without the grid connectivity. It can also listen to 8 channels at a time and comes with fully open hardware and software solutions. Despite being a little more heavier (approximately, 3 kg), it is easy configurable through its web interface and benefit from multiple network servers for data forwarding.

Figure 1.11: Lorrier LR2 Gateway

---

[1] Lorrier LR2:`https://lorrier.com`

1.6.1.7 AllSense EVVOS

Allsense EVVOS is a shock proof and vibration resistant gateway, can be seen in Figure 1.12[1] that conforms to Sigfox specifications and operates on 868 MHz European band. This is one of the unique gateways that comes with a built-in 19000 μAh non-rechargeable lithium battery. As one of the main characteristic, it also has built-in option to support energy harvesting solutions with a deep sleep capability to save further energy. The casing is also strong enough with weatherproof IP66 protection. It can support numerous wireless interfaces in addition to LoRaWAN depending upon the underlaying application requirements.

Figure 1.12: AllSense EVVOS Gateway

1.6.1.8 NB-IoT Smart IO

It is another choice in the LP-WAN family that conforms to the standards of 3GPP release 13 (i.e., NB-IoT and Long Term Evolution for Machine-to-Machine (LTE-M)) (please see, Figure 1.13[2]). It is another cost effective choice that employs Narrow Band networks for remote digital input monitoring mainly for remote metering. It is well capable to provide services for a variety of IoT applications including, but not limited to, smart metering, device monitoring, and SCADA systems.

---

[1] Allsense EVVOS: `https://partners.sigfox.com/products/senseall-sensor-controller`

[2] NB-IoT Smart Gateway: `http://www.m2mserver.com/m2m-downloads/NB-IoT_Smart_IO_Gateway_Datasheet_2017_ENG.pdf`

Figure 1.13: NB-IoT Smart IO Gateway

Table 1.1: A featured comparison of different LP-WAN based gateways currently available in the market

LP-WAN Gateways	**Low Cost**	**GSM Support**	**Well-Documented**	**Sub-GHz Operation**	**Elegant GUI**
Multitech Conduit	x	✓	✓	✓	✓
Embit-EMB-GW1301-O	✓	x	x	✓	x
Kerlink Wirenet 868	x	✓	✓	✓	x
LoRANK 8	✓	x	✓	✓	✓
Link-lab LL-BS-8	x	✓	✓	✓	✓
Lorrier LR2	✓	x	x	✓	x
AllSense EVVOS	x	✓	✓	✓	x
NB-IoT Smart IO	✓	x	✓	x	✓

1.6.2 End-Devices

Just like LP-WAN gateways, there are a variety of choices for the end-devices each characterized by unique features and conforming to different technological specifications. Some of the famous choices are briefly outlined below.

1.6.2.1 Semtech SX127x

SX127x is the most widely used family (as shown in Figure 1.14[1]) to build a variety of LoRa motes because of its compact size, LoRa specifications offering up to 157 dB link budget. It is robust enough to achieve -137 *dBm* receiver sensitivity with an output power of +14 *dBm*. It comes with built-in temperature sensing and low battery indicator and consumes as low as 10*mA* in receiver mode and 100nA for register retention.

Figure 1.14: Semtech SX127x End-point

1.6.2.2 Microchip RN2483

Microchip RN2483 is another famous low power-long range transceiver that can be seen in Figure 1.15[2]. It is readily available in the market for Asian and European frequency bands. The RN2483's LoRa transceiver module provides a compact and easy to use solution with extremely low power requirements for long range transmission/reception of data. Its advanced command interface offers easy configuration and rapid time to market. It also fits well in a range of LP-WAN use-cases providing them a low cost solution [62].

---

[1] Semtech SX127X: `https://www.semtech.com/products/wireless-rf/lora-transceivers/SX1272`

[2] Microchip RN2483: `http://ww1.microchip.com/downloads/en/DeviceDoc/50002346C.pdf`

Figure 1.15: Microchip RN2483 End-point

1.6.2.3 Multitech mDot

Multitech mDot is another secure, certified, and easily programmable LoRa module for a range of low bit-rate and long range M2M applications as shown in Figure 1.16[1]. It is capable to support bi-directional LoRa communication up to 10 miles Line-of-Sight (LoS) and up to 2-3 miles into the buildings and is available for almost all the major markets (such as, Asia, Europe, Australia, and North America).

Figure 1.16: Multitech mDot End-point

1.6.2.4 IMST iM871A

IMST iM871A is another compact radio module (shown in Figure 1.17[2]) in compliance with M-Bus specification EN 13757-4. It has also been declared optimized for a variety of low power applications and easily configurable and accessible via UART interface. It can support a range of up to 3 kilometers in LoS conditions with an output power of

---

[1] Multitech mDot: `https://www.multitech.com/brands/multiconnect-mdot`

[2] IMST iM871A: `https://wireless-solutions.de/products/radiomodules/im871amodule.html`

+14 dBm. It can perform well in different commercial and residential use-cases based on its link budget of up to 120 dB.

Figure 1.17: IMST iM871A End-point

1.6.2.5 NEMEUS MM002

NEMEUS MM002 (in Figure 1.18[1]) is one the first long range module that can support dual modulation. It also conforms to the stands of LoRaWAN A and C classes in addition to Sigfox and is a popular choice due to its compact design, built-in embedded application software, and extremely low power consumption up to as low as 39.5 mA for transmission, 11.7 mA for reception and less than 2 μA while being in the idle mode. The Universal Asynchronous Receiver/Transmitter (UART) interface controls this module and only a few commands are needed to configure it.

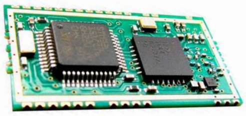


Figure 1.18: NEMEUS MM002 End-point

---

[1] NEMEUS MM002: `https://market.thingpark.com/solutions/tracking/nemeus-lorar-wan-module-mm002-xx`

1.6.2.6 Link Labs LL-RLP-20

It is a highly integrated, bi-directional, and low power gateway, as shown in figure 1.19[1], that is optimized to operate in both 868MHz (EU) and 915MHz(USA) frequency bands. It can acheive a receiver sensitivity of -149 dBm with a transmitting power of 17.5 dBm (60mW). It consumes as low as 1 μA in sleep mode. Their modules employ Semtech's LoRa modulation for range maximization and reducing the power consumption as well as interference.

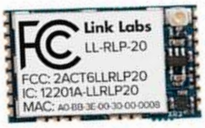


Figure 1.19: Link Labs LL-RLP-20 End-point

1.6.2.7 Adeunis LO868

Adeunis LO868 is another choice in a wide array of radio modules targeting long range with extremely low power consumption as shown in Figure 1.20[2]. It comes with an ease of integration and easily configurable even for non specialists, thus limiting risk factor with development time and costs. it is a certified module that complies with the narrow band specifications to successfully achieve a receiver sensitivity of -120 dBm (i.e., 134 dB link budget).

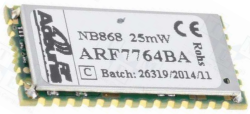


Figure 1.20: Adeunis LO868 End-point

---

[1] Link-labs LL-RLP-20 :https://www.link-labs.com/documentation/ll-rlp-20-or-ll-rxr-27-module-data-sheet

[2] Adeunis LO868 :https://www.tme.eu/en/Document/12436432ddb383ed9be1ab716e498d11/ARF7764BA.pdf

Table 1.2: A featured comparison of different LP-WAN based end-devices currently available in the market

LP-WAN Gateways	**CAPEX**	**Receiver Sensitivity**	**Power Consumption**	**Control Interface**	**Supported Regions**
Semtech SX127x	Low	Medium	Low	No	EU, US, Asia
Microchip RN2483	Low	Medium	Medium	No	EU, Asia
Multitech mDot	High	Medium	Low	Yes	EU, US, Asia, AUS
IMST iM871A	Low	Medium	Medium	Yes	EU
NEMEUS MM002	Medium	High	Low	Yes	EU, US
LinkLabs LL-RLP-20	Medium	High	Medium	Yes	EU, US
Adeunis LO868	Low	Low	Low	No	EU

1.7 Long Range Wide Area Networks (LoRaWAN)

LP-WANs are considered as trendsetters in the evolution of wireless communications thanks to their inherent capability to match coverage, scalability, and energy efficiency requirements of IoT deployments [64]-[65]. In this context, the Long Range Wide Area Network (LoRaWAN) standard recently got a significant attention by the research community and industry because of its rapid adoption for public network infrastructures deployed by several network operators [53, 66]. It integrates the LoRa technology at the Physical (PHY) layer and provides specifications for both MAC and network layers.

LoRa is emerging as a key technology enabler for low power and long range communications [53]. At the beginning, it was particularly intended for low data rate applications developed by a French company Cycleo, later acquired by Semtech. Consequently, it was adopted by the LoRaWAN network architecture, i.e., an open-source standard built on top of the proprietary LoRa physical layer [66]. At the time of this writing, LoRaWAN is a step ahead among other proprietary LP-WAN competitors, right from the inception in terms of its widespread deployments for public networks in European market space, openness of the LoRaWAN standard, and flexibility in the choice of available data rates. The first comprehensive LoRaWAN specification 1.0 was already released back in 2015 [66]. Moreover, a task group under LoRa Alliance is constantly working towards LoRaWAN 1.1 for conceiving more exciting features (e.g., Roaming and Handover mechanism), expected in coming versions [67]. LoRaWAN is now ready to support several use-cases of future IoT services in smart cities, smart home and buildings, smart environment, smart metering, smart agriculture, and many other domains [68].

Moreover, it already covers a lot of important features, including: (i) higher coverage capacity than most of the LP-WAN technologies achievable through Chirp Spread Spectrum modulation scheme; (ii) an adequate data rate for a range of M2M applications exploiting multiple LoRa channels; (iii) extremely low power consumption due to optimized MAC and Physical Layer (PHY) layer design yielding a longer battery life; (iv) tremendous capability to handle thousands of end-nodes through a single gateway; (v) scalability to cater to the needs of all-sized enterprises; (vi) cost effective solutions for both private and public network infrastructures, and (vii) ease of deployment because of the readily available components in the market operated within the Industrial, Scientific, and Medical band.

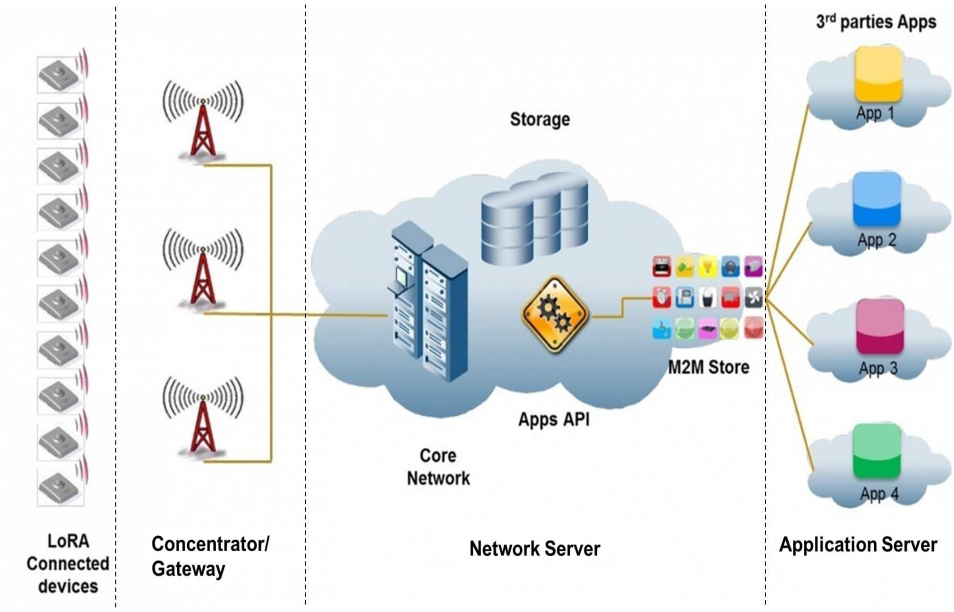


Figure 1.21: Generalized LoRaWAN Architecture

Furthermore, from the system level perspective, LoRaWAN comprises four key components as demonstrated in Figure 1.21: end-nodes, gateways, cloud/network servers, and remote applications [66]. End-nodes may contain any kind of equipment belonging to an IoT system, able to transmit in the sub-GHz band. Gateways act as mediators between end-nodes and cloud/network server. The communication interface established between end-nodes and gateways can simply be referred to as LoRaWAN front-end. Cloud/network servers are responsible for provisioning and managing the network operations (e.g., discarding the duplicate messages), adopting different data rates for end-nodes, and scheduling the downlink acknowledgments. Finally, remote applications control, through the LoRaWAN architecture, the end-nodes and collect the required data by using a simple web interface.

1.7.1 LoRaWAN architecture and node's capabilities

The baseline LoRaWAN architecture follows a simple star-of-stars topological structure, able to offer long radio coverage area. Specifically, a bulk of LoRa end-nodes are connected to one or more LoRa gateways. These gateways are further connected to a remote LoRa cloud/network server. A LoRa end-node may integrate any kind of sensor (e.g., temperature, motion, smoke) belonging to the IoT physical world and it is able to transmit data to LoRa gateways by using the ISM band. Whereas a LoRa gateway is a simple relay device capable of listening on multiple LoRa channels and forward the uplink traffic received from end-nodes to the remote LoRa cloud/network server. LoRa cloud/network server is assumed to be responsible for analyzing and responding to the requests in an appropriate manner after processing. LoRa cloud/network server acts as a centralized entity and can be considered as the backbone entity for the overall LoRa architecture.

It further comprises three main components: LoRa gateway hub, core network server, and LoRa application server. LoRa gateway hub is a part of LoRa cloud/network server that acts as an interface to all LoRa gateways. The core network server is between gateway hub and application server and interacts with the rest of the system through these components. Similarly, LoRa application server is a part of LoRa cloud/network server that enables interaction to the LoRa application. The end-users interact with the system using several LoRa applications that are connected to the LoRa cloud/network server via a simple web interface. Finally, applications can collect their required information by accessing the LoRa server whenever needed. Users can also control the operation of end-nodes by issuing their commands to the end-nodes (through LoRa cloud/network server) as per their rights [66].

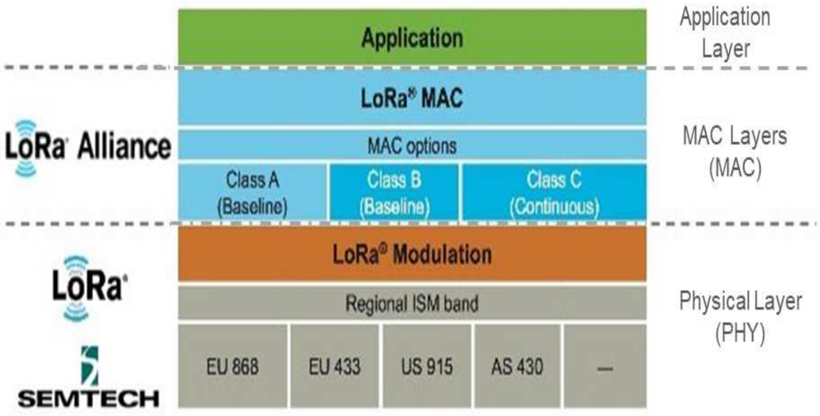


Figure 1.22: LoRaWAN Protocol Stack

1.7.2 LoRaWAN Protocol Stack

There are three fundamental layers of LoRaWAN protocol stack as shown in Figure 1.22. The PHY deals with the electrical characteristics of data transfer at the hardware level. The bottom part is the Radio Frequency (RF) sub-layer in the PHY that defines the ISM bands belonging to different region (i.e., Europe, USA, and Asia) of the universe. LoRa is the physical technology owned by Semtech, a giant manufacturer of the silicon chips, which employs Chirp Spread Spectrum (CSS) as a proprietary modulation technique to make the Physical part of LoRaWAN protocol. While LoRaWAN is the protocol built on the top of LoRa physical technology that is governed and maintained by an alliance of over 160 member companies from around the world including IBM, Cisco, Orange, Actility, and SK Telecom. LoRaWAN deals with the MAC Layer which is responsible for access control, detects changes in the physical to take appropriate actions. The distinction between LoRa and LoRaWAN is significant because different companies have now started using their proprietary MAC on the top of physical LoRa to provide different solutions (such as, Symphony Link) claiming to be better than LoRaWAN. An end-node establishes communication through different MAC commands such as Join request, Join accept, beacon frame, confirmed data up/down, and unconfirmed data up/down. Finally, the application layer corresponds to a range of application layer protocols for the provision of data to the actual LP-WAN applications benefiting these services.

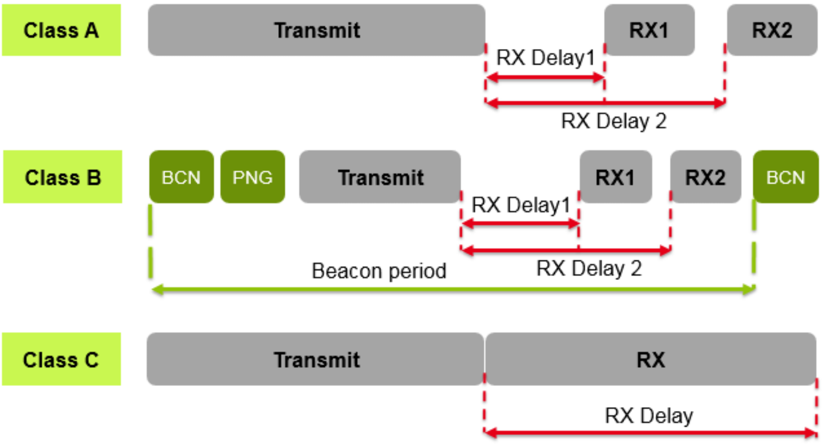


Figure 1.23: Comparison of different LoRaWAN classes

1.7.3 LoRaWAN Classes

End-nodes can be classified into three different categories, namely A, B and, C [69]. Each of them intends to target a certain type of applications, based on their MAC characteristics. The end-nodes belonging to class A, offer a limited reception window (with maximum two receive slots of almost one second duration) for downlink response as demonstrated in Figure 1.23. They are best suited for uplink data-intensive applications (e.g. monitoring applications) yielding longer battery life time [70]. In addition to the functionality of class A end-nodes, class B devices are capable of opening an extra scheduled receive window for downlink response (as in Figure 1.23). An extra beacon is generated to sync the end-node whenever there is a downlink response from cloud/network server irrespective of the uplink packet previously received. This kind of functionality is used in the applications (e.g., actuators) to decouple uplink and downlink communications. Contrarily, class C end-nodes have an always active reception window at the cost of very short battery time causing constant grid connectivity [70]. This kind of functionality is suitable for the end-nodes where a large amount of data is received at downlink as compared to uplink traffic. It is important to note that class A embraces the default functionality that every end-node belonging to the LoRaWAN network architecture should always possess.

1.7.4 Physical transmission and channel access in LoRaWAN

End-nodes and the nearby gateways exchange data through the front-end communication interface, by employing a single-hop and bi-directional (although half-duplex) LoRaWAN communication protocol. Unlike conventional cellular networks, uplink communication is mostly dominant in this kind of networks.

At the physical layer, LoRa supports the choice of a flexible number of channels, bandwidth, spreading factor, and code rate to be used for data transmission [59]. The number of channels and their available bandwidth options depend on the target region and the choice of a LoRa vendor. For instance, up to 10 channels can be used in Europe (commonly 3, 6 or 8 channels are selected in real deployments [71]) and 64 in North America. Nodes may transmit in different sub-GHz portions of the spectrum, HF ISM 868 in Europe and 915 MHz in America, with available bandwidth options of 125 kH0z/250 kHz/500 kHz.

The Spreading Factor (SF) is defined as the logarithmic ratio between symbol rate R_s and chip rate R_c, as reported in Eq. (1.1).

$$SF = log_2 \frac{Rc}{Rs}. \tag{1.1}$$

Typical values span from 7 to 12 and the choice of a given spreading factor provides a trade-off between the data rate and communication range. At the same time, SF allows achieving concurrent communications between several end-nodes and a gateway, without incurring to interference phenomena. This is true even if the same channel is selected. The code rate is the ratio of the forward error correction with the original data stream to be encapsulated. It is chosen among the range of 4/5 to 4/8. It is important to note that LoRaWAN networks may also employ an Adaptive Data Rate scheme if explicitly requested by the end-node to individually manage the data rate and RF output for that end-node. It aims to optimize the lifetime of end-node batteries and the overall network capacity. Alternatively, end-nodes are free to choose any available channel at any given time and available data rate as their default, by means of a pseudo-random channel hopping.

Let T_a be the time required to submit a packet in a sub-band for transmission (also named as Airtime or Time on Air). Then, Airtime, T_a, can be evaluated as:

$$T_a = T_{preamble} + T_{payload} \tag{1.2}$$

$T_{preamble}$, the first part of T_a, is the time taken by a preamble to transmit and can be calculated as:

$$T_{preamble} = (Length\ of\ programmed\ preamble + 4.25) \cdot T_{sym} \tag{1.3}$$

Whereas T_{sym} is the time taken to transmit only a single symbol, expressed as:

$$T_{sym} = 2^{SF} \cdot \frac{1}{BW} \tag{1.4}$$

SF and BW represent the current spreading factor and bandwidth configurations being used. Similarly, $T_{payload}$ is another part of T_a, the total time needed to transmit a payload and can be viewed as:

$$T_{payload} = No.\ of\ payload\ symbols \cdot T_{sym} \tag{1.5}$$

At each transmission attempt, the end-node must comply with the constraints imposed by local regulations regarding the duty-cycle, d, expressed as the percentage of the time during which a channel can be allowed to occupy and consequently, end-node may transmit. Therefore, in addition to the PHY/MAC design of LoRaWAN, the performance of these networks is also affected by restrictions of the duty-cycle [59]. For example, 1% of duty-cycle (which is typically imposed in Europe) implies a maximum transmission time of 36 seconds/hour per end-node. Let T_a and T_s be the time required to submit a packet in a sub-band for transmission (also named as Time on Air) and the time during which the channel is not available for transmission, respectively. In case the channel is not available, the end-node must wait for a time interval equal to T_s before scheduling the next transmission. According to [59], it emerges that:

$$T_s = T_a \left(\frac{1}{d} - 1 \right). \tag{1.6}$$

Hence, the maximum number of packets that a node can transmit in an hour, N_{max}, is equal to :

$$N_{max} = \frac{60 \cdot 60}{T_a + T_s} = \frac{3600}{T_a} d. \tag{1.7}$$

Once the channel is selected by end-nodes with an appropriate SF, the access to the medium is governed by the well-known ALOHA protocol. To analyze the capacity of LoRaWAN networks, it may be assumed as a pure aloha protocol. Here, it is important to highlight two different aspects. First, pseudo-random channel hopping in LoRa uniformly distributes the number of devices over the number of available channels. Second, concurrent transmissions from two end-nodes only encounter a collision if they both select the same SF while transmitting at the same channel. The relatively lower collision probability employing CSS significantly contributes towards improving the overall throughput of LoRaWAN networks for various M2M application scenarios.

1.8 Significance of Energy Harvesting in Long Range Wide Area Networks

1.8.1 Why energy is so important !

As the name implies low energy consumption is one of the main characteristics of this kind of networks [15]. The energy plays a significant role and can be seen as one of the major motivations behind the idea of LP-WAN as it indirectly relates to a lot of other factors (i.e., cost, coverage, and operational efficiency, and environment) that would not have been possible without the low energy consumption, thus it can rightly be said that LP-WAN would be non-existent without considering the role of energy efficiency to make them prominent and practicable.

As discussed earlier, in an effort to build this universe 'a smart planet', the growth of IoT devices is exponential with every passing day where most of the devices perform their operation on AA sized batteries installed. Based on the application requirement, these devices may need to be alive and operational for several days, weeks, months, or in some cases up to years on that battery-powered operation. Hence, it is utmost important to support extremely low energy operation to prolong their battery life for various reasons discussed in details in the following paragraphs.

The battery replacement cost (discussed in details in Chapter 4) in case of battery depletion is another big issue. The replenishment of batteries for that huge number of LP-WAN modules costs enormously and this cast increases exponentially when the modules are installed on harsh locations where, it is difficult to replace the battery(e.g., inside a machinery) and incurs more labor cost.

Although, it is undesirable to replace the batteries in this kind of low cost modules where, sometimes, replenishment costs more than the originally purchased modules, but it is highly application dependent. For example, in many industrial monitoring applications (e.g., anomaly detection), the message frequency is kept higher to avoid the number of damaged products on the production line in case of an anomaly detection at machine. In that case, the cost of damaged products (i.e., damage penalty) can bring more harm than the battery replacement cost, thus it is important to analyze the energy cost keeping in view several interrelated factors.

Moreover, a low-cost infrastructure can be seen as a backbone to make these smart ecosystem use-cases economically viable. Hence, it is important to keep the maintenance cost of such systems as lower as possible. The battery replacement cost is not the only type of cost associated with these systems, but this huge number of sensor modules are also a burden on the energy grids with already scarce energy resources left available to the planet. This extent of growth demands a huge amount of additional energy for the continuous operation which significantly raises maintenance costs.

As the energy consumption has a direct relationship with the radio coverage, thus a variety of LP-WAN use-case demanding truly a wide area coverage, tremendously contribute to increase the energy consumption of these modules. As realized by the Friis Equation:

$$D = \frac{1}{\frac{4\pi}{\lambda} \cdot \sqrt{\frac{P_r}{P_t G_t G_r}}} \tag{1.8}$$

It is obvious from the Eq. (1.8), the more power, P_t, needs to be transmitted to get the higher distance covered, D. It is not that straight forward in case of LoRa as there are also the maximum transmitting power restrictions to transmit in European Sub-1 GHz band [72] (such as, 14 dB or 17 dB for some sub-bands). The nodes have to comply with the restrictions imposed by regional regulatory authorities.

There is also a clear challenge achieving between the performance and energy optimization. As these are the two contrasting objectives and it is impossible to achieve them both at the same time [73]. There might be several IoT use-cases (such as, delay-critical ones) where performance parameters are more important than the energy optimal operation. Achieving a battery life of end-nodes lasting for years becomes even more complex in this trade-off situation.

Finally, the more number of drained batteries needed to be dispose-off, the more the cost and carbon footprint. With this huge growth, the wastage of a huge number of batteries is not an environment-friendly approach on the top of more cost incurred to disposing-of the old batteries. Hence, it is always desirable to prolong the battery life of these modules employing different techniques (such as, energy harvesting technologies).

Energy-harvesting techniques have recently gained a lot of attraction being a separate parallel source of energy available to them system. It is been exploited towards almost all the technological areas without exception. Anticipating the future and high energy demand of LP-WAN technologies, the time has come to seek the ambient sources of energy whose potential is already present in the environment and they are well capable to solve most (if, not all) of the energy issues in an era where energy has become more crucial and scarce as it has never been before.

1.8.2 Examples of some energy exhaustive LoRaWAN use-cases

As the LoRaWAN is flexible offering a number of LoRa configurations (such as, data rate options with different spreading factors), the exact amount of energy consumption is still application dependent. In general, higher the distance covered, the higher the energy consumption. As discussed earlier (details in Section 1.4), there are a lot of LP-WAN use-cases targeted by LoRaWAN but few of them are more energy exhaustive (outlined below) as compared to others.

1.8.2.1 Industrial

In most of the industrial use-cases like anomaly detection and predictive maintenance, the message frequency can be quite higher with the intension to keep the expert systems updated for timely decision making that may cause depleting the batteries of LoRaWAN devices earlier than expected. This trade-off has been studied in great detail in Chapter 4 where prolonging the sensing interval not only reduces the battery replacement cost, but it also causes a huge financial loss in terms of number of faulty products manufactured in that damage interval.

1.8.2.2 Healthcare

Similarly, as per the requirements of several healthcare applications, the frequent readings of the various healthcare indicators (such as, body temperature, blood pressure, sugar level, and many others) are taken to ensure their urgent treatment in case of sudden variation recorded among these readings marking them abnormal. The smart healthcare systems generate urgent alerts for all the stakeholders in case of abnormality. Here, the reading between these readings can neither be longer nor it can be up to the choice of developer, as the human lives are involved and any delayed decision can never compensate the possible loss in that case.

1.8.2.3 Real-time tracking

Real-time asset tracking can also be seen as a relatively energy exhaustive use-case. For example, the owner/company may want to continuously monitor their remote vehicles and the activities of their drivers at any point in time to analyze their current status and to optimize the movement of vehicles on the basis of smart decision making that can eventually induce business intelligence. This kind of operation may prove to be energy exhaustive and there is a need to look for a parallel energy solution on the top of battery-powered operation.

1.8.3 Factors affecting the lifetime of LoRa motes

After having a look at different energy exhaustive use-cases of LoRaWAN, it is also important to understand the different phenomena affecting the lifetime of LoRa modules. Some most common actors are outlined.

1.8.3.1 Choice of right hardware and connectivity

It is undoubtedly right and equally important to deeply study and design the hardware of these modules to make them optimum for the energy consumption. Nevertheless, it is not the only hardware that can dramatically make the difference but connectivity of the modules and message transport can also save an enormous amount of energy. Different vendors available in the market report different consumption readings for their hardware. Similarly, each technology belonging to an LP-WAN paradigm exhibits different energy consumption for their chipset.

1.8.3.2 Operating cycle

Operating/duty cycle is the most important and perhaps most studied method to save some amount of energy. It refers to switching off the radio or putting it to sleep whenever possible to save some amount of energy. Although tuning the duty-cycle is the most easiest and conventional way of energy saving but it is not always possible achieve duty-cycled operation as desired due to the application requirements. On the other hand, duty-cycle operation may not be enough for the nodes to save ample amount of energy and we need to optimize some other parameters on the top of duty-cycled operation.

1.8.3.3 Message frequency

As discussed earlier, message frequency is one of the factors that directly influence the energy consumption. The target market for most of the LP-WAN technologies are the applications with low message frequency requirement per unit time. There are also the duty-cycle restrictions in place to ensure the equal share of bandwidth among plenty of end-devices competing for the access. Due to regional duty-cycle limitations, LP-WAN technologies are unable to support use-cases demanding very frequent communication.

1.8.3.4 Acknowledged communication

Although most of the LP-WAN technologies including LoRa support bi-directional communication (i.e., both uplink and downlink), uplink traffic is almost dominant in the use-cases employing this kind of technologies. Despite of downlink provision available, there is a limited possibility of downlink traffic (e.g., only after each uplink slot in LoRaWAN class A devices). Therefore, acknowledged communication is not possible all the times using these technologies and doing so wastes an extra amount of energy that is not at all desirable unless strictly needed. LoRaWAN class C devices are best suited for data-critical applications with always opened reception windows at the downlink on the cost of higher energy consumption. This type of devices are usually grid-powered and can be used for acknowledged transmissions.

1.8.3.5 MAC operation

Optimized MAC operation is also one of the key aspects that explicitly affects the energy consumption [73]. Sensible MAC operation can save an ample amount of energy at hand to prolong the battery life but, unfortunately, in case of LP-WAN technologies like LoRaWAN, selection of a complex MAC protocol is not beneficial. It may instead provide more harm than good in LoRaWAN because even the energy consumed during complex MAC operations (e.g., sensing) is not affordable. Therefore, an ALOHA type of simplistic MAC protocol is deployed in most of the technologies in this category.

Moreover, several parameters (such as, bit error and collision rates) also impact the energy consumption that are usually related to MAC operation.

1.8.3.6 Data rate and radio coverage

Finally, as the LoRaWAN is flexible with respect to the choice of several configuration parameters (i.e., data rate, payload size, code rate), thus choosing these parameters also affect the energy utilization of LoRa radio. For example, choosing a lower spreading factor (e.g., SF7) may consume least amount of energy on the cost of short radio coverage. Contrarily, the signal transmitted over a higher spreading factor (e.g., SF12) would surely reach more distances on the cost of low data rate and high energy consumption.

1.9 Summary

The chapter starts with overviewing the IoT concept and discusses this most important technological transformation from devices to things in detail with some of the recent challenges to this paradigm. It further highlights the space for LP-WAN in a broad area of IoT and how well the LP-WAN are fit into that space as compared to a number of other alternatives looking at some of the most important dimensions of LP-WAN technologies. It further discusses the evolution of these LP-WAN starting the technological journey from last century's renowned short range wireless technologies (such as RFID, NFC, Bluetooth) to some of the modern technologies (e.g., Wi-Fi and cellular systems) and what are the motivations behind LP-WAN in the presence of a pile of popular technologies. Then, some of the most important domains of prospective applications of LP-WAN are presented discussing several use-cases of each domain in great detail.

Moreover, several design considerations for LP-WAN technologies are highlighted discussing the detail about how each candidate is different from other with respect to these considerations. The following section provides an insight for the real LP-WAN based products including both the gateways and the end-points solutions belonging to different LP-WAN candidates. Furthermore, the LoRa technology and the LoRaWAN are discussed in great details with a special focus on its architecture and nodes capabilities, protocol stack, end-node classes, physical transmission and channel access mechanism in LoRaWAN. Finally, several energy issues are surveyed in LoRaWAN domain and the significance to explore the parallel ways of energy are highlighted presenting different energy exhaustive use-cases and throwing light of the critical factors directly influencing the lifetime of these modules.

2

Energy Harvesting MAC Protocols for Sensor Nodes: Challenges and Tradeoffs

A critical facet of Energy Harvesting-Sensor Nodes (EH-WSNs) lies in the interplay between Energy Harvesting (EH) techniques and Media Access Control (MAC) protocols. In fact, while EH technologies feed motes with energy, the MAC layer is responsible for a significant quota of spent energy because of message transmission/reception and channel sensing operations. In addition, the energy brought by EH technologies is not easily predictable in advance because of time-varying nature: this makes the design of the MAC protocol even more challenging. To draw a comprehensive review of the state of the art on this subject, this chapter first provides a detailed analysis on existing energy harvesting systems for Wireless Sensor Networks (WSNs); then it extensively illustrates pros and cons of key MAC protocols for EH-WSNs with a special focus on: fundamental techniques, evaluation approaches, and key performance indicators. Finally, it summarizes lessons learned, provides design guidelines for MAC protocols in EH-WSNs, and outlooks the impact on Internet of Things (IoT).

2.1 Wireless Sensor Networks and their prospective applications

A collection of tiny nodes capable of sensing the environment, performing simple computations and supporting wireless communications to accomplish a monitoring task can be referred to as WSNs. After almost a couple of decades since their emergence, WSNs have been adopted in almost all possible areas including, but not limited, to Smart Homes [74], Smart Healthcare Systems [48, 75], Intelligent Transportation Systems [76], Disaster Management Systems [77], and Continuous Video Surveillance Systems [78].

Nowadays, WSNs are broadly used to set up distributed monitoring infrastructures in self-healing, self-configuring, and self-managing systems. They are composed by many elementary devices (or motes) equipped with basic sensing, computing, and communications capabilities, which interact on a collaborative basis to sense a target environment and report collected data to one or more sinks. WSNs are expected to be operational for very long periods of time, even if each mote cannot bring large energy storage units. Accordingly, Energy Harvesting mechanisms can greatly magnify the expected lifetime of WSNs. Over the years, EH-WSNs have been thoroughly studied by the scientific and industrial communities to bridge the gap between the vision and the reality.

Lifetime is the Achilles' heel of WSNs: in fact, network nodes (also known as motes) are usually battery operated and spend a remarkable quota of energy to handle wireless communications primitives [79]. To avoid a frequent replenishment of batteries, it is necessary to optimize all the operations running in each single mote and quite a few approaches have been proposed so far in this direction [80]-[82]. Nevertheless, the experimental evidence demonstrates that WSN lifetime is never enough [79].

2.2 Essential background and related works

The bulk of proposed approaches to optimize the living time of conventional battery-powered WSNs include but not limited to energy-aware MAC protocols (SMAC [83], BMAC [84], XMAC [85]), routing and data dissemination protocols [86]-[88], power aware storage, duty-cycling strategies [89, 90], adaptive sensing rate [91], tiered system architectures [92]-[94], and redundant placement of nodes [95, 96].

Energy harvesting technologies [97]-[99] can significantly prolong WSN lifetime by converting solar, wind, vibrational, thermal or RF energy into electrical energy. Their disruptive potential has led to the formulation of the so called Energy Harvesting-Wireless Sensor Networks (EH-WSNs). The effectiveness of EH-WSNs mainly depends on the interplay between EH technologies and the protocol stack (as explained in Sec. 2.4.1).

MAC protocol always plays a significant role in the design of WSNs as major energy consumption is due to the sensing, reception, and transmission process. Accordingly, a special attention has been paid to MAC protocol design [100]-[102] and a wide hierarchy of protocols has been proposed for WSNs.

With EH-WSNs, MAC design becomes even more challenging because the pattern of energy harvested from the environment is not easily predictable in advance. Although, it can be predicted up to short or medium time intervals that can be of the order of microseconds to hours (e.g. harvesting solar vs RF) depending on various factors including but not limited to application, topology, energy harvesting technique, and the environment but, even then, MAC protocol has to seek the best tradeoff between Quality of Service (QoS) and energy efficiency at run time based on the actual status of motes. The proposals formulated so far (and thoroughly discussed in Sec. 2.5) differ to each other with respect to many features and design principles that deserve an in-depth analysis.

Unfortunately, most of the surveys [100],[103]-[109] available in literature describe MAC protocols for plain WSNs but only a couple of them [110, 111] approach EH-WSNs by simply overviewing the functionalities of a very limited number of protocols without providing the current challenges and tradeoffs for the performance optimization. They do not either deal with the pros and cons of specialized MAC protocols for EH-WSN that are vital for understanding their limitations. To the best of our knowledge, there is not a single study available in literature to date correlating the characteristics of energy harvesting technologies with the performance of specialized MAC protocols for EH-WSN because each specialized protocol may behave differently when employed against different harvesting technologies.

To bridge this gap, a detailed analysis on the need for special MAC design (Sec. 2.3), energy harvesting technologies (Sec. 2.4.1), and MAC protocols for EH-WSNs (Sec. 2.5) is proposed hereby. A list of motivations for a special MAC design instigating the need for special type of protocols is presented in Sec. 2.3. Moreover, for each technology described in Sec. 2.4.1, the key implications on EH-WSNs are discussed. The pros and cons of the protocols proposed in Sec. 2.5 along with a general classification taxonomy is presented that highlights their similarities and differences based on number of parameters. Some open issues and lessons learned related to MAC protocols for EH-WSN are discussed in Sec. 2.6 highlighting the challenges and future research opportunities. Finally, a brief summary of the chapter is presented in Sec. 2.7.

2.3 Motivation for special MAC protocols targeting EH-WSN

As the plain MAC protocols are not capable to undertake the requirements imposed by EH-WSNs, it is inevitable to consider special MAC protocols customized for EH-WSNs. To gain a thorough understanding of the problems associated with plain protocols, it is significant to understand how plain WSN are different from EH-WSN and why the plain MAC protocols behave inappropriately for EH-WSN. MAC protocols already available in the literature for non-energy harvesting WSN are intended to prolong the network lifetime by avoiding the following energy exhaustive operations[112]:

- **Sensing:** when a shared medium is used, the sender senses the channel before transmitting to reduce the probability of generating a collision.
- **Contention:** when multiple nodes simultaneously have data to transmit on the shared medium, a contention stage is entered to limit the impact of collisions .
- **Transmission:** Similarly, after the successful contention, nodes undergo actual transmission of data to their intended nodes.
- **Collision:** e.g., Hidden or Exposed Terminal Problem.
- **Idle Listening:** Listening the channel with no packet.
- **Overhearing:** Receiving unintended messages.

- **Control Packet Overhead:** Control message or extra payload fields.
- **Over Emitting:** Sending while receiver is not ready.

We may significantly reduce the level of energy consumption by adapting specially tailored MAC protocols for energy harvesting networks. On the other hand, special MAC protocols for EH-WSN aim at achieving the best trad-eoff between uncertain energy conditions and longer network life with optimum performance. There are multiple factors that instigate the need for a special type of MAC protocol intended for EH-WSN presented throughout this section.

2.3.1 Design Principle

There exists a fundamental difference in the design principle of EH-WSN with respect to battery-operated WSN as the later were developed with the intention to achieve longer life times. Contrarily, energy harvesting paradigm relaxes the power constraints faced by battery-operated WSNs and the focus of EH-WSN is rather to improve the network performance (i.e., throughput, delay, inter-arrival time etc.) operating in a sustainable energy state. Hence, the design principle differentiates the need for a special MAC protocol that should be designed keeping in view the performance requirements (i.e., targeting QoS improvement instead of longer lifetime) of EH-WSN.

2.3.2 Adaptive Duty-cycle

The individual nodes in plain WSN usually undergo a common duty cycle because of the obvious energy availability as they are equipped with a battery, gradually goes on decreasing with time. Instead in EH-WSN, the actual amount of energy at hand at any given instance is not straight forward due to certain environmental limitations of harvesting mechanisms. Hence, the MAC protocol design for EH-WSN demands for an adaptive duty-cycle of individual nodes as compared to a system wide common duty-cycle based on their individual energy availability at hand. This special kind of MAC protocol would enable the low energy nodes to manage their operations (switching between sleep and wake-up mode) independent of the global system inducing flexibility of operation.

2.3.3 Harvesting Capabilities

Unlike plain WSN, end-nodes in EH-WSN are equipped with harvesters that enable them to scavenge some amount of energy from the environment. On one hand, it helps these nodes to continue their ongoing operations but, on the other hand, it may be challenging for the nodes because the harvesting capabilities are not the same for all the nodes in an EH-WSN. This variation may be due to several factors including harvesting mechanism, time, environment or the precise position of the harvester. For example, the amount of energy harvested by a node equipped with solar cells positioned in direct sun radiations would be different compared to the node coincidently placed in a shadowed area. The special MAC protocol should be designed to smartly compensate the lower energy nodes making available the surplus energy harvested by the nodes with higher capabilities.

2.3.4 ENO-MAX State

Energy Neutral Operation (ENO) mode of a node ensures that consumed energy is always lesser or equal to the amount of harvested energy for a node. A node refers to the ENO-MAX state when it is able to achieve ENO mode yielding the maximum level of performance. Unlike simple MAC protocols, the special protocols for EH-WSN are designed to support a node towards achieving ENO- MAX state. As the level of energy availability varies for different nodes belonging to EH-WSN, it is extremely important to tune the existing MAC protocols with respect to the instant energy level of individual nodes towards achieving performance optimization.

2.3.5 Energy Characteristics

It is important to note that WSN exhibit very different energy characteristics as compared to EH-WSN. The energy level in battery operated-WSN reduces with time and they are continuously operational until zero energy level. Contrarily, nodes belonging to EH-WSN usually consume higher energy (in their routine operations) than they can harvest in certain periods of time. Hence, a certain level of energy accumulation is recommended using the storage before starting with the normal operation of EH-WSN. This characteristic behavior offers (theoretically) unlimited amount of energy to EH-WSN that makes them suitable for many energy intensive applications [77, 78] demanding extended battery life-time. It is inevitable for the designers to incorporate these dynamics to the special MAC protocols for EH-WSN.

2.3.6 Variable Charging Profiles

MAC protocol plays its part in achieving optimal, fair and, timely monitoring achieved by the coordination of sensor nodes that requires the nodes to stay awake as maximum as possible. As discussed above, the charging time for all the nodes varies depending on the environment, time and type of the harvester. The nodes go asleep while they charge enough battery to accomplish their ongoing operations. It puts another constraint towards traditional MAC design that directly influence the performance metrics. Hence, this new set of MAC design considerations for EH-WSN sets them apart from the plain WSN and special MAC protocols for EH-WSN (described throughout in Section 2.5) are based on the new design constraints imposed by energy harvesting architectures.

2.4 Research on Energy Harvesting

This section discusses about different types of energy scavenging mechanisms specifically used for WSNs along with system architecture and design alternatives for EH-WSNs.

2.4.1 Energy Harvesting Mechanisms

The concept of renewable energy dates back to centuries and it has been the most widely used way of energy transformation before the invention of coal. Many natural energy sources have been known till date [113, 114] but the mechanisms of energy scavenging and storing are still a challenge in some cases. These days, the most common sources of ambient energy harvesting are solar, thermal, wind, and water that transform different forms of energies to electrical energy. Unfortunately, energy harvesting for low power devices (like in WSNs) is challenging because of the size compatibility of harvesting devices with the small motes. Designing the circuits for energy harvesting devices is fairly complex task because of being highly dependent on the type of energy source, energy storage devices, power management capabilities, protocols used, and underlying application's requirements. Solar, vibrational, electromagnetic, thermal, wind, and RF energy sources are the few known ways of ambient harvesting from the environment for WSNs where the research efforts [115] have been extended with special emphasis as shown in Fig. 2.1

Figure 2.1: Few known sources of harvesting energy available in the environment

Table 2.1 presents a clear comparison of maximum power density possible from each kind of energy harvesting technologies.

2.4.1.1 Solar

The solar power sources are the most widely used ambient energy sources [115] due to their readily available and consistent energy scavenging capabilities in the light hours with a mere disadvantage of non-availability of their operation in night times or bad weather conditions. This kind of harvesting mechanisms usually employ a single or double level storage capacity (e.g., battery or super-capacitor) for ongoing operations even in the absence of harvesting hours. The circuit designed for this kind of source converts light energy into an electric current. Research efforts have been spent [125] for supporting WSNs because the classic solar systems were not designed to cope with modern challenges of WSNs. To prevent the energy wastage during the transfer from harvester to sensor, Maximum Power Point Tracker (MPPT), a tracker circuit [126] has been proposed to effectively transform the newly harvested energy with minimal

Table 2.1: Comparison of maximum power density from energy harvesting technologies

Harvesting Method	Power Density	References
Solar energy-outdoors	$15mW/cm^3$-bright sunny day, $0.15mW/cm^3$- cloudy day	[116]
Solar energy-indoors	$6\mu W/cm^3$	[117]
Vibrations (piezoelectric-shoe inserts)	$330\mu W/cm^3$-105 Hz	[118]-[120]
Vibrations (electrostatic conversion)	184 $\mu W/cm^3$-10 Hz	
Vibrations (electromagnetic conversion)	$0.21\mu W/cm^3$-12 Hz	
Thermoelectric ($5-20^o$C gradient)	40μ W -10mW/cm^3	[121]
Magnetic field energy	$130\mu W/cm^3$-200μT, 60 Hz	[122]
Wind energy	$65.2\mu W/cm^3$-5 m/s	[123]
Ambient RF Energy	0.08nW-1$\mu W/cm^3$	[124]

power loss.

2.4.1.2 Vibrational

Vibrational or mechanical source [115] of ambient energy harvesting is due to the motion of certain objects according to Faraday's law of electromagnetic induction that may sometimes be referred to as kinetic energy. This source of scavenging the energy is being deployed growingly by many advanced WSNs applications ranging from button press [127] to the shoe sensor [128]. The latter is fed by harvested energy due to the force exerted by human walk which serves various types of WSN applications fulfilling the energy needs of a certain sized information packet. Similarly, a traffic sensor [129] becomes operational for a reading due to the amount of energy produced when a vehicle passes through that sensor. The results show that the amount of energy acquired from these sources is sufficiently enough keeping in view the needs of applications requiring seldom operation.

2.4.1.3 Electromagnetic

This is another type of harvested energy by different frequency radio signals when a node is exposed to electromagnetic field. A sufficient amount of energy can be obtained by the use of inductors to feed various types of WSN applications [115]. According to Tentzeris et. al. [130], there are various electromagnetic energy scavenging sources around us in this universe but humans are unable to get into them. Furthermore, such kind of sources have been explored using ultra-wideband antenna to achieve higher power gains. It is believed that this technique may open up new horizon for the researchers working in this particular area [130].

2.4.1.4 Thermoelectric

Due to the potential difference or gradients of temperature between two poles of the same material, thermoelectric harvesting is made possible that is pretty common in a variety of prospective applications these days [115]. For example, the temperature reading of a human body and the environment around it because the kind of devices having direct contact with body may harvest an amount of energy using Thermogenerators [131]. The design of such micro-structured devices has been proposed [132] to cater the energy demand of communication and embedded applications. These devices may be able to last for relatively longer than vibrational devices because of lesser movements of objects.

2.4.1.5 Wind

This form of energy harvesting has always been challenging in WSNs due to the size incompatibility of wind turbines with regard to sensor applications [115] that adds yet another constraint in the deployment of this technology in WSNs. The focus of the work in this area has been on the large-scale energy harvesting and only few research articles consider it for small scale harvesting applications [133]-[136]. The major flaw associated with wind energy is unreliability due to the non-constant and unpredictable behavior of wind hence it is unable to harvest the equal amount of energy all the times. Moreover, it might suffer electrical noise due to the movement in the mechanical part of turbines.

2.4.1.6 Ambient RF Energy

Although, this kind of energy scavenging exhibits very low power density but it can be harvested with full potential employing high gain antennas. Ambient RF sources keep on increasing with the great expansion of broadcasting infrastructure hence, it has become a valuable source of energy available almost every hour throughout the day.

The higher power densities can be achieved especially in the urban areas and within the closed proximity of radio sources (e.g., Base Stations or Broadcasting Towers) [124]. It provides the most appropriate way to recharge the sensor nodes deployed at a location (e.g., Home Automation or Structural Health Monitoring applications) where it is difficult to substitute the batteries frequently. The distance between the power source and the harvester can significantly affect the efficiency of the total power output. Similarly, non-line of sight sources, power output from RF source, path loss, shadowing, fading and, RF-DC conversion efficiency are also some major downsides of this kind of techniques [124].

2.4.2 Energy Harvesting Architecture

Energy harvesting architecture can be referred as the combination through which various components in an energy harvesting system may combine and interact together to achieve an optimal performance level. Before going into the details of possible combinations and their corresponding interactions, it is important to have a look at the entities involved in an EH-WSN system. Fig. 2.2 shows the overall architecture depicting various components of the energy harvesting system and their interactions. Energy harvesting architecture can be seen as the combination of three fundamental components; Load, harvesting source and, harvesting system. The brief details on each of the components is presented in this sub-section covering basic operations and how these components interact with each other to achieve optimum performance level.

2.4.2.1 Load

It can be seen as an energy consuming process in the system such as a sensor node in the WSN. A node generally consumes energy in the activities such as, sensing, contention, transmission, collision, idle listening, overhearing, control packet overhead, and over emitting as discussed above in the section 2.3. We may significantly reduce the amount of energy consumed by the load by adopting especially tuned MAC protocols (as thoroughly discussed in Section 2.5).

2.4.2.2 Source

Source can be seen as any harvesting technology being used such as solar, wind, vibrational or thermal or other alike technologies capable of extracting ambient energy from the natural sources. The amount of harvested energy at the source side plays a vital part in the overall system design because it can exhibit unpredictable and time-varying dynamics that strongly affect the lifetime of a WSN. The literature [113, 114, 137, 138] clearly emphasizes that no single source can be sufficiently enough for all kinds of applications in WSNs. Accordingly, the characteristics of WSN applications need to be in the exact accordance with the type of harvesting technology being used.

2.4.2.3 Harvesting System

This is the most crucial and significant part of the architecture. It serves as a mediator between the source and load, keeping in view energy consumption/generation profiles and application requirements. As inbound and outbound energy flows cannot be deterministically known in advance, the harvesting system should be designed based on worst case conditions. It can also be seen as an energy management module that stores excessive energy when the inbound flow is larger than the outbound one to face under-provisioning periods. It is also capable of tuning the load profiles (e.g., altering the data rate) to achieve optimal performance level. In distributed system paradigms, it plays a crucial role where all the individual nodes may have different sources of energy and locally oversee their needs. Here, energy saved at one node may play an important role to make the other nodes operational when they are out of their local energy hence to make the overall architecture as robust as possible.

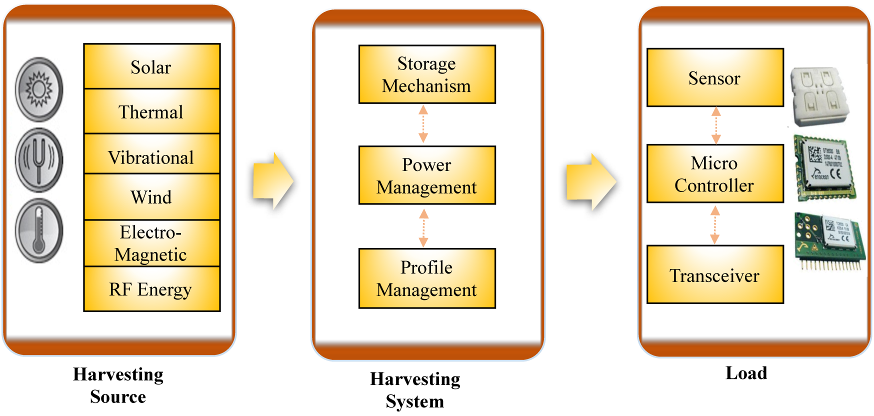


Figure 2.2: Energy harvesting architecture

Power management aspect is as important in EH-WSNs as the harvesting process itself because the ultimate goal is to come up with a best tradeoff between performance and life time. In conventional power control mechanisms, the primary design consideration was to extend the battery lifetime as maximum as possible. In EH-WSNs, instead, the key design goal has turned out to be performance as a whole rather than battery conservation only. In this context, the prediction policy for future energy availability is the key to optimum decision making process and it is required at various stages of the operational system [139].

A similar predictive approach has also been proposed in [140] emphasizing that quick learning of the adoptive energy environment and energy sources can be exploited efficiently using the already collected information. Further contributions in [141, 142] also argue the adoption of power management with an ultimate goal of achieving optimal performance of WSNs without the consideration of only battery life.

Power management module in harvesting system widely plays its part in achieving ENO. It refers to a situation of an EH-WSN where the rate of energy scavenging is always greater or equal to the amount of energy being consumed or it satisfies the underlying consumption profile [141]. It can also be regarded as when the amount of harvested energy on source is always greater than the amount of consumed energy by a load then the system is said to be in ENO. ENO is the foremost objective to be achieved by today's WSNs that lets the designers to further move onto the performance maximization in the next stage. This kind of systems may have various distributed components bearing their own set of harvesting sources where the entire performance does not depend on the local profiles of available energy but it is always regarded as how this energy is used to ensure an optimal network wide performance.

2.4.3 Harvesting Design Alternatives

We argue that harvesting system design is equally important as MAC Protocol design because it is nearly impossible to come up with a desired performance level considering only one of them. Fig. 2.3 classifies different design alternatives that will be further explored within this sub-section. A comparison of different features related to the energy harvesting systems for these design alternatives are presented above in Table 2.2.

Table 2.2: Comparison of features for possible design alternatives of WSN

Sr. No.	**Alternative 1**	**Alternative 2**	**Alternative 3**
Candidates / Characteristics	**Store-Consume WSNs** [80]-[102]	**Harvest-Store-Consume WSNs**[103]-[109]	**Harvest-Consume WSNs** [127]-[129]
Design Flexibility	A tradeoff between Latency and Throughput for longer network lifetime.	Achievable long lifetime by backing up the battery power with energy harvesting and energy management techniques.	Due to the availability of renewable energy, no threat to lifetime and it is possible to achieve optimal throughput with suitable delays by applying some techniques.
Energy Prediction	Sleep and wakeup schedules can precisely be predicted.	Sleep and wakeup schedules are predictable depending upon the future energy availability prediction.	Sleep and wakeup schedules are not easier to predict because of uncertainty of future energy availability.
Energy Model	Energy Model is well understood.	Energy model can be predicted to accuracy controlling some aspects.	Energy model highly depends upon the EH rate across time, space as well as type of harvesting source.
Protocol Design Challenge	Protocol may perform well within the lifetime constraints.	Protocols can exhibit adequate performance being parameter specific, not in general.	Protocol can be environment specific because of high variations and unpredictability in the context.

2.4.3.1 Store-Consume Alternative

This is the conventional architectural style existed in WSNs as shown in Fig. 2.3(a) where small sensor nodes are equipped with a compatible sized battery storage containing a sufficient amount of energy required to keep the node operational for as long as possible keeping in view the type and energy demand of underlying application. The focus in this kind of scenarios is prolonging the lifetime by optimizing the protocol stack: clearly delays and throughput can be impaired in order to save energy and prolong the WSN lifetime. For example, sensors belonging to a fire detection system deployed in a forest are usually equipped with a small storage buffer aimed at prolonging the life time as best as possible.

2.4.3.2 Harvest-Store-Consume Alternative

Adding up the harvesting system leads to a set of complexities and tradeoffs in addition to the major advantage of energy scavenging mechanism as shown in Fig. 2.3(b). Energy harvesting sensor nodes with a storage technology exploit the advantage of potentially unlimited amount of energy availability where the focus can fearlessly be turned towards the performance parameters of the system instead of energy hence the tradeoff between energy and performance is a bit relaxed in these WSNs. Although harvesting system imposes the challenge of energy uncertainty at a particular time T due to the random energy arrivals but a range of protocols has been proposed [119, 140] to achieve predictable sleep and wake-up schedules of communicating nodes to cope with this problem up to some extent.

The interplay of power management and topology control strategies seems relevant in EH-WSNs. In fact, if a sufficient amount of energy is not available to a particular mote to be operational, it would eventually turn to sleep mode to harvest some amount of energy for future operations. Generally speaking, several nodes may at a time be switched between sleep and active (wake-up) modes simultaneously that would cause a frequent topological variation. This alteration may impair the performance of the WSN. Different strategies for sleep and wake-up schedules have been analyzed in [143] based on various aspects (such as, channel or battery state, queue-based and solar radiation-based) keeping in view the context and, a game-theoretical approach to find out optimum parameters for sleeps and wake-up schedules is also presented [143].

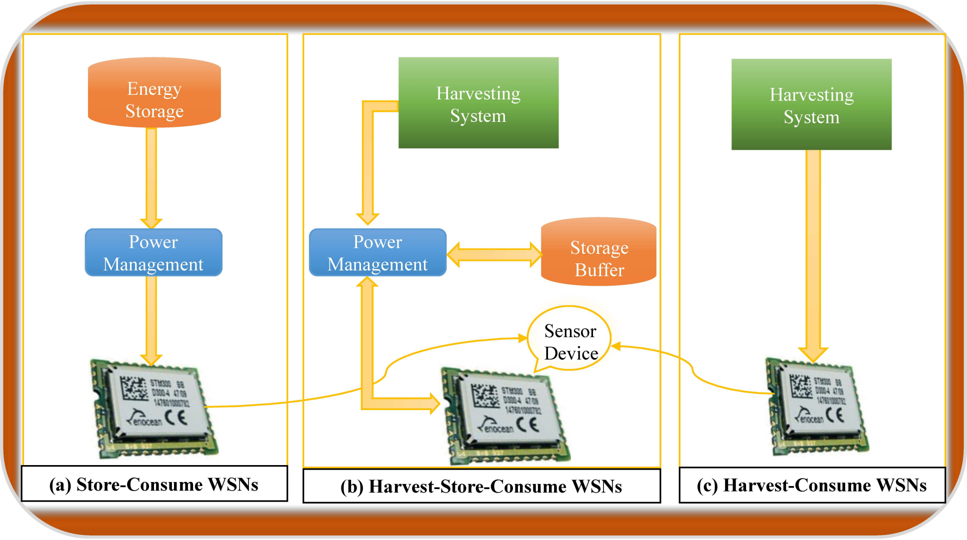


Figure 2.3: Energy supply alternatives for wireless sensor networks

The added advantage can be achieved by inducing a global distributed energy management module that employs more than one type of energy harvesting systems and keeps track of the exact amount of energy utilization on any node at time T and saves the extra amount of energy harvested for future needs of the same node or to compensate the need for another node when it is energy deficient. A range of today's IoT applications (such as, smart cities, smart agriculture as well as smart industries) employ this kind of alternative where a lot of efforts have been made towards prolonging the life time of end nodes [103]-[109].

2.4.3.3 Harvest-Consume Alternative

Another widely used approach is to have the harvesting system on the node but newly harvested energy is directly provided to node for its operations without an intermediary energy storage buffer as depicted in Fig. 2.3(c). Since energy is directly provided through renewable sources and there is no storage limitation hence no threat to the lifetime of the system. It lets the designers to focus on achieving the optimal throughput and delays (i.e., performance parameters) relaxing the overhead of energy storage and management module present in Fig. 2.3(b).

The main challenge towards this approach is the energy wastage. When the harvested energy is greater than the consumed energy, the extra energy is simply wasted.

Contrarily, in case of lesser harvested energy than the energy required for a node to perform certain action, the amount of newly harvested energy goes to the wastage due to the absence of storage. Here, it becomes difficult to schedule the sleep and wake-up intervals for communicating nodes because of unpredictable nature and amount of energy being harvested.

Energy availability in this kind of scenarios is highly dependent upon the time, environment and the type of harvesting technologies. Several use-cases in wellbeing monitoring applications [127, 128] follow this kind of architecture. For example, the energy harvested from the pair of shoes during the walk/running can be utilized to transmit some important readings taken by the temperature, heart beat or blood pressure sensors to the application server. Similarly, energy harvesting from a button press can be fed to a sensor belonging to smart home applications.

2.5 Special MAC protocols for Energy Harvesting-Wireless Sensor Networks

This section aims at covering the current state of the art of various MAC protocols present in the literature for energy harvesting-wireless sensor networks. It focuses on the fundamental design, several evaluation methodologies and key performance indicators considered by this set of protocols. Various pros and cons of these protocols keeping in view the future design considerations are also highlighted. Finally, a comprehensive comparison is drawn among all these protocols towards a clear vision of what we have in literature at the moment and what should be the orientation of possible future research in this area. As we have already discussed in previous sections, there is a rich variety of categories for MAC protocols in general based on various parameters to differentiate one type by another, Fig. 2.4 presents a clear overview of the hierarchy of MAC protocols specifically customized for EH-WSNs based on the duty-cycling techniques and the initiation process.

It is worth mentioning that synchronous MAC protocols are not deemed appropriate for EH-WSN because of different duty cycle requirement for individual sensor nodes caused by variable energy availability. For example, a sensor node running out of energy could not be woken back as promised by synchronous schedule. Hence, only the asynchronous MAC protocols are considered in this study for EH-WSN. These

MAC protocols for EH-WSN can be classified into three main categories with respect to duty-cycling techniques and the initiation process as in Fig. 2.4.

Moreover, MAC operation becomes critical in EH-WSNs and the protocols proposed in this area behave differently in the presence of each energy harvesting mechanism (discussed in sub-section 2.4.1) with respect to different application requirements. For example, as a constituent of smart home application, a carbon dioxide sensor to estimate the crowdedness of space has been developed [144] where the appropriate ventilatory measures (e.g., opening up the window) are taken in case of suffocation. The prototype is based on $RTX4100$ powered by artificial indoor light bulbs. The MAC operation in this scenario follows a basic duty cycle. Initially, the process starts by assessing the energy availability based on the voltage comparison of storage buffer with the preset threshold. In case of sufficient energy at hand, it polls out for the reading. If the reading is significantly different than the previous one and it is above a particular threshold measurement, it consequently transmits that reading to take appropriate actions and goes back to sleep until next cycle. The study investigates the performance of prototype in presence of both; a non-energy harvesting (IEEE 802.11) and energy harvesting protocols (On-Demand Medium Access Control (ODMAC) [152], discussed later in this section). The study concludes that the sustainable energy-efficient operation, with different input power levels, is only possible with energy harvesting MAC protocol.

Although, majority of protocols discussed throughout this section, do not seem to be built on each other but they share common design principles highlighted in classification taxonomy presented in Figure 2.4. They further aim at achieving the common characteristics shown in Table 2.4. As per the brief chronological evolution, energy harvesting protocols were initially proposed in all three categories shown in Figure 2.4 including single-hop probabilistic polling [145], MTPP [146], ODMAC [152] and SEHEE-MAC [162]. Then, Multi-hop Probabilistic Polling [151] was built on Single-hop probabilistic polling [145] extending the same concept for multi-hop communication. Then, QAEE-MAC [155] was proposed being the first ever EH-MAC protocol targeting QoS. A huge bunch of protocols was customized in the middle era exploiting two right most techniques in Figure 4 (e.g., LEB-MAC [153], ERI-MAC [154], ED-MAC [156], DeepSleep [159], EL-MAC [161], and RF-MAC [163]). RF-MAC [163] targeted the same QoS parameters in addition to achieve energy optimal operation as compared to QAEE-MAC [155]. Here, ED-MAC [156] employs similar dual filtered scheme like DeepSleep [159] and EL-MAC [161]. Similarly, some protocols have been proposed lately in recent couple of years in two most right categories shown in Figure 2.4 including RF-AASP [147], AH-MAC [148], and SyWiM [157] where last two also support multi-hop communication.

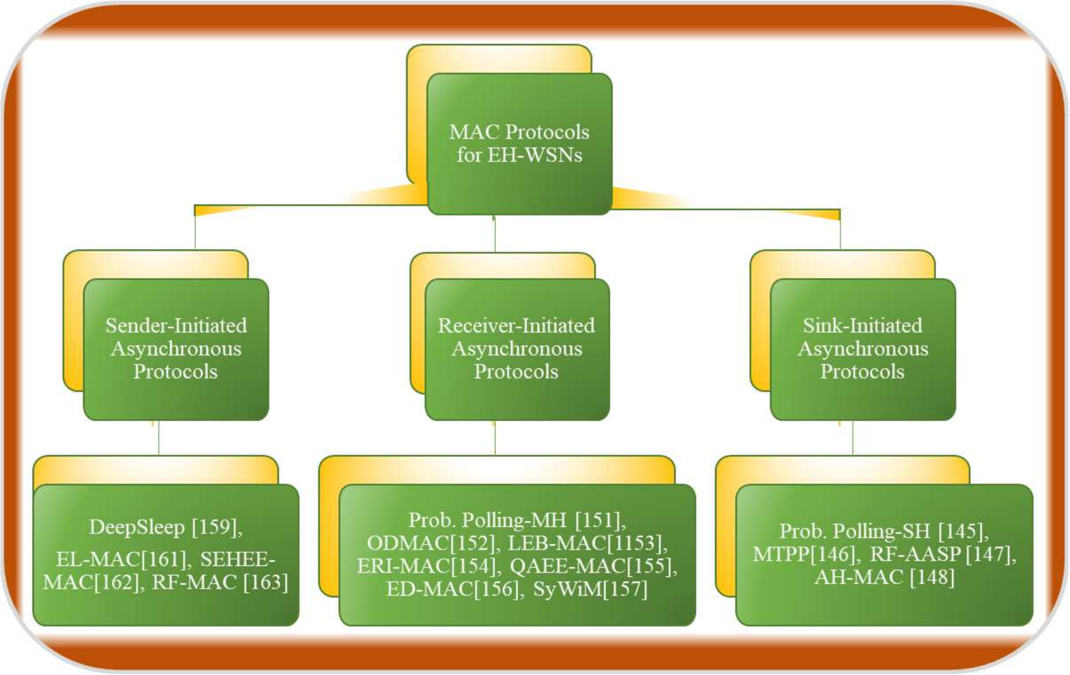


Figure 2.4: Categorization of MAC protocols for EH-WSNs

Most of the protocols presented in Fig. 2.4 can be seen in the category of receiver initiated protocols because of the following reasons. First, receiver-initiated protocols successfully reduce the major overhead incurred due to the collision between two contenders in a sender-initiated protocol that causes a significant delay to slower down the protocol initiation process. Second, receiver-initiated protocols make the new data exchange possible just after completing the previous exchange without going into sleep which, on the other hand, speeds up the ongoing communication yielding better performance. The special MAC protocols for EH-WSN are analyzed throughout this Section under the same taxonomy presented in Fig. 2.4.

2.5.1 Sink-Initiated Asynchronous MAC Protocols

2.5.1.1 Probabilistic Polling for Single-Hop WSNs

A Probabilistic Polling approach for single hop WSNs is presented in [145] where several experiments are set up to emphasize that the rate of harvested energy is directly related to many aspects such as time of the day, location of harvester, and the source of harvested energy. As discussed in the previous sections, the abrupt variation in energy arrival rates needs some kind of adaptation in every MAC protocol design for EH-WSNs to handle the harvesting dynamics. A sink initiated paradigm is presented in [145] where sink node incorporates harvesting dynamics by announcing the contention probability i.e., P_c based on the current energy levels of nodes while the nodes below this probability will automatically be out from the pool of contending nodes and they will have to wait for the next polling. Whenever a node is out of residual energy, it would not take part in contention switching to the charging state to harvest enough energy for future operations.

Pros: The contention probability follows Additive Increase Multiplicative Decrease (AIMD) policy for the number of nodes that are currently in active state. If the sink does not receive any data packet from any node in response to polling, it would increase the polling probability of next cycle considering that there are not enough nodes in contention. Conversely, polling probability would be decreased if there are collisions within the system. This yields higher throughput, scalability and fairness and it well handles the collision situations by probability adjustment leading to the fair source allocation.

Cons: Although probabilistic polling approach responds appropriately to dynamic energy harvesting conditions, it may take too long to converge in a frequently changing environment. In fact, if a bulk of nodes joining and leaving the system abruptly causes frequent changes in increasing or decreasing the contention probability then nodes may either face collisions or may not get the opportunity of transmitting data due to that probability fluctuation. This causes latencies and leads to wastage of energy and bandwidth in the long run. Additionally, this protocol only supports single-hop communication scenarios assuming that next receiving node would be the intended destination while that is not always the case in EH-WSNs as there may be several relay nodes involved responsible for onward transmission of the data packet towards intended destination.

2.5.1.2 Multi-Tier Probabilistic Polling (MTPP)

Building on the probabilistic polling approach discussed in [145], MTPP [146] is another protocol with the extension towards achieving multi-hop data delivery that employs a tiered hierarchy model with a cluster of sensor nodes formed based on the distance from the sink. Tiers are represented by natural numbers ($Tier_1, Tier_2, Tier_3...$) comprising a group of nodes ($n_1, n_2, n_3...$) in each tier. Sink is responsible for broadcasting a polling packet to $Tier_1$ nodes (the closest ones). One of the nodes from $Tier_1$ would be chosen to broadcast this packet to the next tier nodes above it and it would start waiting for the data packet to be received and so on for the next tiers in hierarchy. An 8-bit tier number is incorporated within the polling packet. Initially, all the immediate neighbors of the sink are associated with the $Tier_1$ and rest of the nodes are assigned tier *255* that can be the maximum possible tier number. The nodes then gradually identify their corresponding tier looking at the polling packet.

Pros: A fixed polling interval of 33ms has been used [146] to ensure the end devices receive the polling packet within an interval when their radio is on because it is not feasible for the end devices to turn on its radio all the times due to a limited amount of energy at hand hence radio control is another significant feature of this protocol. Moreover, dynamic tier assignment is also one of the novelties of MTPP as end devices sometimes suffer interference offered by other devices (e.g. based on WiFi) which causes some nodes to push them from $Tier_1$ to $Tier_2$ due to their inability to listen to the polling packet remaining in $Tier_1$.

Cons: The evaluation of MTPP is done on a 2-tier scale considering the simplest case but the authors are unsure about the performance exhibition on large scale only hoping the effectiveness of the protocol for dynamic network scenarios. It can be an obvious fact to limit the scenario with as minimum number of tiers as possible because large number of tiers would eventually affect by incurring an overhead of polling packets that may lead to increasing collisions within the system causing wastage of significant amount of energy.

2.5.1.3 Radio Frequency based Adaptive, Active Sleeping Period (RF-AASP) MAC

RF-AASP [147] presents a technique to dynamically adapt the active sleeping period to switch the sensor nodes harvesting more energy from the ambient RF energy sources in the environment. This scheme adapts the active sleeping period depending on multiple factors such as varying traffic loads, residual energy of individual sensor nodes and, the estimation of RF energy available from surrounding. This approach intends to minimize the contention level and maximizes the probability of energy harvesting which results not only improving the energy efficiency but also the network throughput. The sink node is responsible to estimate the current traffic conditions by counting the number of incoming packets from an IoT application in current Beacon Interval (I_b) and compares it with the number of packets in the previous (I_b) to estimate the actual variation for tuning the QoS parameters. This kind of schemes usually employ two different antennas at the sensor nodes; one for harvesting the required RF energy while the other for the actual communication. Power management unit on each sensor node is the decision-making entity that finalizes either the node has to activate antenna *1* to recharge itself through RF energy in the harvesting interval or it has to use antenna *2* to transmit the data in the transmission period.

Pros: The foremost concern of RF-AASP protocol is to consider two important aspect of energy efficiency and QoS achievement and it seeks the best trade-off between them as compared to other protocols (e.g., QAEE-MAC [155]) striving to optimize only one of them. FR-AASP presents a comprehensive analytical. model for RF energy harvesting process, energy consumption model and, incoming harvesting RF energy estimation. This protocol assumes variable traffic conditions for tuning the sleeping period which eventually provides flexibility to the MAC design targeting QoS achievement.

Cons: RF-AASP assumes only a $25m$ radios for deploying RF energy harvesting source (eNodeB) and harvester in their simulation study [147] which does not seem to be a realistic assumption for the evaluation of this approach through simulation. The best way to evaluate the RF energy harvesting could be to deploy the real test beds towards a precise estimation. The evaluation comparison of this protocol was drawn with another MAC protocol (i.e., ABSD) proposed for non-energy harvesting WSN that may not be justifiable in this respect.

2.5.1.4 AH-MAC: Adaptive Hierarchical MAC Protocol for Low-Rate Wireless Sensor Network Applications

Adaptive Hierarchical MAC Protocol [148] is another sink initiated protocol suitable targeting low data rate applications for large scale wireless sensor networks. AH-MAC is built on Low-Energy Adaptive Clustering Hierarchy (LEACH) [149] and IEEE 802.15.4 [150] and does its job by exploiting the advantages of each of them. AH-MAC considers only a fraction of end nodes (only cluster heads) equipped with energy harvesting circuit while rest of the nodes in the network are kept battery operated. Consequently, AH-MAC shifts most of the network activities to cluster heads leaving the rest of the nodes with minimal job aiming to prolong the lifetime of nodes in the presence of battery-supported operations. AH-MAC follows hierarchical routing with sink being the grandparent and all other nodes are further divided into cluster heads and followers. Initially, the sink starts sending its beacon at the start of its frame and stays alive until the active period has elapsed. It then goes back to sleep until the start of the next slot and the first child cluster head starts sending its beacon in the second slot. Similarly, the second child cluster head sends its beacon in the third slot and so on. Thanks to this mechanism, only one cluster is active at a time and all other are sleeping that prevents cluster interference. Every cluster head has to wake twice during a frame; first during the slot of its parent to stay synched with parent and upload its data and, second in its own slot to send the beacon and let its followers upload their data.

Pros: As AH-MAC well exploits the many of the advantages of 802.15.4 [150], it is capable to outperforms conventional LEACH protocol in terms of energy efficiency and delivery ratio when considering low data rate use-cases. Unlike LEACH where the node is active throughout the whole frame, the active time in AH-MAC is limited to only one slot as compared to conventional LEACH which results in saving a reasonable amount of energy.

Cons: This approach successfully reduces the energy consumption of nodes on the cost of increased energy consumption of cluster heads which are assumed to be connected with unlimited energy harvesting source while this assumption seems to be unrealistic because each energy harvesting source may have its own limitation and cannot be seen as source of unlimited energy at any given time. Secondly, in case of a cluster head failure in this kind of approaches, the election for a new cluster head can appear to be a bottleneck because the followers would not be able to upload their data even if they have enough energy unless a new cluster head has been chosen that would lead to wastage of useful resources along with incurring delays within clusters.

2.5.2 Receiver-Initiated Asynchronous MAC Protocols

2.5.2.1 EH-MAC Probabilistic Polling for Multi-Hop WSNs

An enhanced version [151] of the probabilistic polling technique discussed above [145] was also proposed from the same authors for multi-hop communication scenarios common in EH-WSNs. Another solution formulated for the same problem has been presented in this protocol emphasizing on the idea of the number of neighbors currently active for contention probability adjustment. All the nodes taking part in the contention wait for a random time between 0 and t_{max} and try sending the polling packets only if they sense an idle channel. The polling probability P_c is included in the packets that plays its role in deciding which nodes are eligible for transmission in that specific cycle. A new probability adjustment technique Estimated Number of Active Neighbors (ENAN) is employed in addition to AIMD in this protocol. Contention probability in this protocol can also be seen as inversely proportional to the number of active neighbors. Moreover, the receiver decreases contention probability where a collision occurs assuming that there are more estimated number of active neighbors than the system is expecting. Similarly, the value of contention probability tends to increase where nodes encounter an empty slot and no one takes part in contention for transmission.

Pros: This protocol exhibits improved throughput and latency just like its first version for single hop WSNs and is pretty scalable for traffic loads, energy scavenging rates and various density levels of network. On the top of it, EH-MAC enjoys an added advantage of employing ENAN approach for contention probability adjustment in addition to AIMD that offers more control as compared to other duty-cycle tuning schemes.

Cons: Due to the lower contention probabilities, it is more likely for the nodes to wait for longer period of time before getting their first opportunity to transmit in higher network densities. It is even worse in multi-hop scenarios where nodes have to wait for longer because of each intermediary relaying node towards destination which causes a greater end-to-end delay within network. In addition to the problem of inefficient convergence with frequently changing topologies, it also suffers in terms of energy, bandwidth and time wastage in case of no or corrupted response.

2.5.2.2 On-Demand Medium Access Control (ODMAC)

ODMAC [152] is a prominent MAC protocol for EH-WSNs initiated by the receiver with periodic beacons towards the intended senders. These beacons inform the senders about readiness of receiver to receive their responded packets. As soon as the senders receive these beacons, the transmission would instantly be started. This protocol is based on the duty cycle adjustment and opportunistic forwarding techniques to reach the ENO-MAX state (energy neutral state when harvesting energy fully compensate the consumed energy keeping in view the performance) after which the protocol claims to achieve an optimum performance level. Duty-cycle can further be adjusted by two different methodologies; beacon period adjustment and sensing period adjustment. A node with extra harvested energy can decrease either the beacon or sensing interval (time between consecutive beacons or sensing operations) and the deficient energy nodes can contrarily increase either of these parameters based on the type of application and its requirements. The node can further tune either of the intervals in case of extreme energy shortage. Each node maintains a list of relay nodes in opportunistic forwarding and sends the packet instantly whenever it receives a beacon by the list members avoiding the need of keep waiting for a particular receiver.

Pros: ODMAC makes best use of the energy harvesting by duty-cycle adjustment to achieve improved end-to-end delay and sensing reliability. Minimal energy is wasted on idle listening by employing opportunistic forwarding mechanism which helps the node forwarding their packets as soon as possible. They define a new approach named binding mode where extreme low power nodes are hard bound with the duty cycle of a particular node to further prevent it going in dead state.

Cons: The technique in ODMAC is based on the current information in hand regarding system state and does not support smart decision making based on future predictions for the adjustment of duty-cycles. On the other hand, the newly introduced binding mode in ODMAC requires having a complete information regarding the duty-cycle of intended binding receiver that is not easily feasible in EH-WSNs.

2.5.2.3 Load and Energy Balancing MAC (LEB-MAC)

LEB-MAC [153] is another receiver initiated protocol that informs the senders by broadcasting a receiver beacon carrying the wake-up schedule of receiving node. Keeping in view the information just received by beacons, senders schedule their wake-ups a bit prior to the wake-up schedule of their intended receiver. In the beginning, senders do not have any concrete information about their receivers but they have the ability to learn the schedules by subsequent transmissions. However, the maximum possible waiting time (SL_{max}) for a sender to learn this information is application dependent and the duty cycle adjustment always functions keeping in view the residual energy level of the node. Fuzzy logic has been proposed to formulate appropriate sleep intervals keeping in view the energy level of the nodes. The collision scenarios have been divided into two types; occurrence of a collision when none of colliding nodes have prior communication history with receiver and collision where some senders have already communicated with the receiver in past cycles.

Pros: Each receiver maintains a list of its prospective senders including those who have previously communicated with this receiver and it sends a dedicated beacon to the sender list if it involves a second type of collision. If more than one colliding sources are present in its senders list, the receiver would send a beacon to schedule the next transmission based on the information obtained from last cycles hence introducing a priority mechanism. Energy consumption is intelligent in LEB-MAC because of the known wake-up scheduling of receivers. As the receivers serve as senders for some other nodes so it smartly plays with the duty cycle of other nodes keeping in view the energy level that would end up towards achieving fairness and load balancing in a system.

Cons: As the first time senders do not have any scheduling information about their intended receivers so the amount of waiting time in this case is non deterministic and they would have to wait for all the previous communicating senders to finish their communication before getting a transmission opportunity for them hence they may experience much longer delays in their first communication cycles leading towards slowing down the system. The issue might be even more serious to be faced in dynamic networks where the new senders are more probable without even having an energy prediction mechanism.

2.5.2.4 An Energy-Harvested Receiver-Initiated MAC (ERI-MAC)

ERI-MAC [154] is another recently proposed receiver-initiated MAC protocol for EH-WSNs that basically uses Carrier Sense Multiple Access (CSMA) - Collision Avoidance (CSMA-CA) as a channel access mechanism. It is quite similar to Probabilistic Polling schemes and ODMAC discussed above [145, 152] in this section in terms of fundamental operation in addition to its readily available support for large scale network conditions having realistic traffic patterns. It comes up with a new dimension of super packet resulted in merging various smaller packets together to reduce the overhead incurred by separate headers for individual packets. This protocol makes use of the packet queueing technique to achieve Energy Neutral Operation (ENO) state by delaying a packet for a safe duration. Safe duration can be seen as the amount of time spent by a packet in a (FIFO) data queue to ensure the residual energy is always greater or equal to the consumed energy required during packet transmission.

Pros: The protocol offers a value feature of packet concatenation presenting a concept of super packet where the primary purpose of this long packet is to successfully reduce the header overhead in case of smaller packets. The novelty of ERI-MAC is its retransmission support (reasonably significant for EH-WSNs) in addition to conventional contention handling that differentiates this protocol from the counterparts leading it to a step ahead towards achieving QoS in data critical applications.

Cons: While attempting to reduce the header overhead by a super packet, protocol may compromise the usefulness of this feature due to maximum size bound limitations by some radio platforms (such as, IEEE 802.15.4 CC2420 [150] can maximum support 127 bytes of data packet). The protocol was evaluated on a real testbed of 49 node grid in ERI-MAC and the performance can be compromised in the situations where the size of the network is non-deterministic in the start of some applications due to higher dynamicity of a network.

2.5.2.5 QoS-aware Energy-Efficient MAC (QAEE-MAC)

QAEE-MAC [155] is another receiver-initiated protocol with the aim of achieving QoS improvement that employs data priority mechanism where the packets with differentiated importance may be transmitted faster than the normal data packets ensuring urgent communication for critical applications. In this protocol, sender indicates the importance of its data through broadcasting a beacon just after waking up from sleep and waits for the receiver's response. Consequently, the receiver wakes up a bit earlier to collect all beacons of this nature just to know the importance level of each sender keeping in view the communication urgency. The receiver then prioritizes the list of senders and responds by broadcasting a beacon containing the ID of the currently selected sender letting it to transmit while all other nodes tune themselves to go for sleep for the duration of this transmission to avoid interference.

Pros: The protocol offers a precise priority assignment mechanism and the receivers beacon in response not only broadcasts the new priority assignment decision but also acknowledges the previously accomplished communication similar to the functionality of ERI-MAC [154] that is perhaps a desperately needed feature for toady's WSNs. Moreover, nodes keep track of their energy level while scheduling their duty cycles in QAEE-MAC.

Cons: The evaluation studies show that the protocol suffers in terms of performance because it is experimented with only one receiver and few senders in a single-hop way and may experience long delays in case of large scale network scenarios. Secondly, the priority assignment mechanism also causes significant energy consumption in terms of idle listening at all the senders that may eventually prove to be a bottleneck for such energy critical nodes who are already in a low energy situation and require to be handled with great caution.

2.5.2.6 Exponential Decision based Medium Access Control (ED-MAC)

ED-MAC [156] is fundamentally based on residual energy of each individual sensor node and tunes the adaptive duty-cycles for all the sensor nodes individually. Just like DeepSleep [159] and EL-MAC [161], it also employs two different kind of filters. In the first phase, exponential MAC is solely based on the current state of residual energy of an individual node. The node is assumed sleeping in the initial stage. It wakes back and calculates its residual energy. This scheme evaluates the slop of the decision graph to know the status of energy availability on each node by comparing it to different preset energy levels (i.e., maximum residual energy (E_{max}) and threshold residual energy (E_{th})). Then, it calculates the maximum off time (T_{dc}) for each individual node that dynamically increases or decreases depending on the residual energy. In the second phase, this protocol takes into account the prospective residual energy that a node is expected to harvest in a course of time. The off time (T_{dc}) of an individual node can be squeezed based on its estimate of future energy availability.

Pros: This protocol not only considers the current residual energy but also employs mechanism to estimate the future energy availability at individual nodes. This prediction capability makes possible to tune the duty-cycles of individual sensor nodes dynamically. Consequently, it enables sensor nodes to maximize their performance keeping in view not only the current residual energy but also the energy availability in future. It compares the various performance metrics (e.g. end-to-end delay, average energy consumption and, packet delivery ratio) with another static receiver-initiated MAC protocol supporting linear dynamic duty-cycle approach. Results show that ED-MAC exhibits better energy utilization and management as compared to its counterpart.

Cons: The evaluation procedure shows that the protocol suffers in terms of performance in multi-hop scenarios because it is experimented on very small scale with a single-hop fashion and may experience long end-to-end delays in case of large scale network scenarios. Secondly, every time a node wakes up, it compares its residual energy to different preset energy levels. If the residual energy remains lesser than a particular threshold, the node would again go to sleep. It causes the wastage of bandwidth, energy and duty-cycle of individual nodes that may yield delays in the overall system. Third, this kind of schemes are application dependent and behave differently for each topological structure. They do not fit well in the applications experiencing frequently changing network topologies.

2.5.2.7 Synchronized Wake-up Interval MAC protocol (SyWiM)

SyWiM [157] is another receiver initiated protocol proposed targeting on two significant aspects; timing offset and clock drift to improve the overall QoS. Timing offset may occurs if the nodes are deployed at different times during initialization or resynchronization phases while clock drift refers to the frequency deviation of local oscillator. SyWiM employs solar panels as the source of renewable energy assuming sun light during the sunny day and light bulbs in the indoor environment at night times or during cloudy days with 24h periodic pattern. In SyWiM, whenever a node has data, it waits for the wake-up beacon from the associated receiver. As soon as the beacon is received, it transmits the data after clear channel assessment and calculation before transmission operations. The receiver may confirm the receipt of this packet by sending an acknowledgment back to the sender before going to sleep. Due to the difference in timing offset, the first communication between nodes incurs long idle listening intervals that are reduced to normal interval from the next communication after the first communication has successfully been taken place. During the second time, the transmitter is able to find out the exact timing offset and accordingly updates the next wake-up interval. Similarly, the next wake-up deals with the clock drift after resolving timing offset. For this purpose, the transmitter wakes up an interval p prior to the wake-up schedule of its receiver to maintain synchronization where p is equal to the maximum possible clock drift between the nodes.

Pros: SyWiM successfully improves many QoS parameters (like data rate, latency, energy consumption). The experimental setup of SyWiM not only involves simulation platforms but the authors also validate their proposal with real WSN hardware platforms considering PowWow [158] as the potential candidate. Moreover, SyWiM adopts super capacitors as storage mechanism that exhibit increased number of recharge cycles up to 500,000 as compared to conventional battery powered solutions [157] which also contributes towards prolonging the battery life of sensor nodes.

Cons: Although, SyWiM improves many QoS metrics but the authors [157] exhibit the usefulness of their proposal considering a network size of up to 50 nodes only. In case of large deployments, the performance may severely be affected. Moreover, three different energy harvesting profiles are considered that are randomly selected among the pool without any mechanism that may not be suitable in some scenarios where the amount of energy in hand may not be equal to or less than the amount of harvesting energy (selected harvesting profile) assumed for supporting the continuous operation.

2.5.3 Sender-Initiated Asynchronous Protocols

2.5.3.1 DeepSleep; An 802.11 Extension for EH-M2M

DeepSleep [159] can be seen as an extension to IEEE 802.11 Power Saving Mode (PSM) [160] specifically designed for Energy Harvesting Machine-to-Machine (EH-M2M) communication with the mere provision to support large scale EH sensor networks compared to other variety of protocols present in this area. The MAC protocol design considerations for M2M communication are quite similar to WSNs hence, many proposed schemes for M2M are stimulated by WSNs. In 802.11 PSM [160], time can be seen in terms of beacon intervals that are further divided into Ad-hoc Traffic Indication Map (ATIM) window and transmission intervals. If a node has some data destined for another intended destination, it first exchanges a pair of ATIM packets (request and acknowledgment) with corresponding next hop and all other devices switch to sleep mode except this pair of nodes woken-up for rest of the beacon interval. The devices going below a particular energy threshold will observe DeepSleep to save energy at hand and to harvest sufficient amount of energy for future operations. This protocol further introduces another filter approach named Controlled Access in which newly woken-up devices from DeepSleep would further compete with peer nodes to reduce the number participating in the contention process. It further enhances the chance of participating devices to fairly get a transmission opportunity.

Pros:

The primary advantage brought by these techniques may be the reduction of number of active nodes participating in the contention leaving the rest of nodes in better (lower) contention situation. The devices woken back from sleep in result of applying both of these mechanisms are assigned a shorter contention window for the sole purpose of prioritization of nodes to get the channel sooner. Consequently, it may lead to a reduction in collisions, overhearing and idle listening.

Cons:

The probability to go back to sleep for all the nodes in controlled access is equal including those that have just woken back after DeepSleep. Although the protocol favors the newly awoken devices by assigning a shorter contention window to enable them avoiding a longer contention before transmission but it is equally likely that a node would be forced to go DeepSleep even if it has just woken back. These forced slept nodes would again harvest more energy even if they already had sufficient amount of energy for their prospective transmissions. This phenomenon would starve the nodes with higher energy level for fair channel access in comparison to other contending nodes within the system.

2.5.3.2 Energy Level based MAC (EL-MAC)

EL-MAC [161] is another sender initiated MAC protocol presented for Energy Harvesting Secondary Users (EH-SUs) in Cognitive Radio Sensor Networks (CRSN). The operation in CRSN is performed based on the exploitation of spectrum holes during the utilization period of Primary Users (PUs) without interfering the ongoing process initiated by PUs. EL-MAC takes a whole super frame as a combination of sensing, contention and transmission periods. If an SU finds the channel busy during sensing period, it immediately goes to sleep, otherwise, it further proceeds to take part in the contention period. If the contention is successful based on the Differentiated Access Probability (DAP), it enters in transmission period to go ahead with the transmission leaving behind other contending nodes. This protocol uses CSMA/CA as a channel access method in addition to Differentiated Access Probability (DAP) and Differentiated Contention Window (DCW); two newly introduced filters. SUs compute their DAP which is supposed to be inversely proportional to their current energy levels turning some users to sleep mode. The second filter (DCW) is applied to existing nodes to further enhance the probability of medium access for low energy nodes switching few more nodes on sleep.

Pros:

As EL-MAC forces some nodes going to sleep based on their residual energy so it successfully enhances the contention level for the rest of the nodes leaving them fewer in numbers. EL-MAC provides special provision to low energy nodes to best utilize their residual energy and ensures the minimum amount of energy is wasted during contention and idle listening if a low energy node has packets for transmission. It further offers the energy saving for high energy nodes turning them to sleep even if they have sufficient energy level, they may harvest a bit more energy instead of wasting their own.

Cons:

The mechanisms employed by EL-MAC always pushes the high-energy nodes out of contention hence they are switched on sleep mode not only to save some energy but to harvest an additional amount of energy. Consequently, these nodes always remain high energy nodes that may eliminate their chances for accessing the medium for their own transmissions and they may never get the transmission opportunity being in high energy level. Moreover, as mentioned in ODMAC [152] and DeepSleep [159], this protocol is also intended for single-hop WSNs where the destination is one hop away. But in multi-hop WSNs, one may not be sure about the transmission success because of not having the current state of the intended receiver.

2.5.3.3 Solar Energy Harvesting Energy Efficient MAC (SEHEE-MAC)

SEHEE-MAC [162] assumes solar energy as the renewable source and introduces the notion of slotted preamble technique to control the radio over a sensor node. It can save the significant amount of energy by reducing the duty-cycle of individual sensor nodes based on their energy status and switching the low energy nodes on sleep mode. A sender initiates the process by sensing the channel employing CSMA type basic mechanism. If the channel is idle, it keeps on sending the slotted preamble unless all the neighboring nodes turn on and receive the preamble for at least once. The intended receiver would acknowledge back with a request to send the full packet back to the sender. As soon as the sender receive the full packet request, all the other nodes turn off their radio switching themselves to sleep mode while sender successfully transmits full packet. After each successful transmission, the residual energy of sending node is compared to minimum energy threshold. It increases the slotted preamble interval if the threshold is reached or keeps on sending the full packets otherwise. The node would calculate its back-off interval if it senses a busy channel unless it reaches the maximum back-off limit.

Pros:

Unlike conventional preamble techniques, SEHEE-MAC employs slotted preamble technique to control the radio activities of a sensor node which helps to save an adequate amount of energy. A solar based energy harvesting system is also studied along with this MAC approach conforming to the energy requirement imposed by habitat monitoring applications. An analytical energy model is also proposed to evaluate the precise energy requirement in case of both energy harvesting and battery-operated WSN for different traffic conditions.

Cons:

In an attempt to reduce the energy consumption, SEHEE-MAC undergoes some serious limitations. The neighboring nodes turn their radios on just after the reception of preamble and keep on listening until they receive acknowledgment by a receiver with full packet request which causes idle listening. Moreover, SEHEE-MAC is also topology specific and does not fit well in the applications with frequently changing topologies. The evaluation procedure shows that this protocol was compared with other non-energy harvesting protocols instead of a logical comparison with the similar counterparts.

2.5.3.4 A Radio Frequency based MAC for wireless energy harvesting in WSN (RF-MAC)

RF-MAC [163] strives to identify how different factors (such as placement, selected frequency range and, the number of RF energy transmitters) impact the charging time through ambient RF energy. These factors are considered while designing RF-MAC which not only minimizes data transmission disruption but also optimizes the energy delivery to the nodes. The sending node undergoes channel sensing employing fundamental CSMA access technique and waits for Distributed Inter-Frame Space (DIFS) amount of time. Here, it is important to note that DIFS is defined separately in RF-MAC for both data and energy transfer. Sensor nodes with higher energy harvesting rates have shorter charging durations. Sensors with greater residual energy are assigned a higher priority for the data transmission yielding optimal network lifetime. Similarly, RF-MAC introduces the notion of adaptive back-off period where the nodes with greater residual energy experience the shorter back-off time as compared to low energy nodes. The contention window is randomly selected for the data exchange between a range of minimum and current window values. This selection of contention window is independent of the residual energy of the sensor nodes which helps to prevent Convoy Effect (preventing nodes with higher residual energy to always occupy the channel that puts all the lower energy nodes on wait).

Pros:

RF-MAC not only deals with the energy harvesting and MAC design but also emphasizes on wireless energy transfer employing the idea of collaborative beam forming of distributed transmitters on the top of IEEE 802.15.4 mechanism [150]. It also attempts to optimize the power output employing high-frequency signals with different phases in order to improve the energy efficiency. Furthermore, this scheme is not only evaluated employing real testbeds (i.e., MoCA2) but it also justifies the performance comparison through simulations [163].

Cons:

In an attempt to optimize the power output using high-frequency signals with different phases, time synchronization for high-frequency signals may always be a challenge in this kind of protocols. Moreover, the scheme is evaluated in comparison with two different approaches. One of them is modified CSMA which is actually a non-energy harvesting approach hence inappropriate for the evaluation.

2.6 Open issues, Challenges, Lessons Learned and Future Research Directions

Each protocol discussed so far was aimed at catering to one or two specific aspects bearing a clear set of advantages and disadvantages. Different application requirements and design considerations were also taken into account. Summary of the techniques used by these protocols to make them compatible for EH-WSNs is presented in Table 2.3. The hop count and validation method for each energy harvesting MAC protocol have also been indicated after a detailed study on the protocols. Nevertheless, all the protocols (discussed in the Sec. 2.5) experience several critical issues of general nature in addition to their individual pros and cons. This immediately translates to a new set of challenges and opportunities that will be explored in this section.

To draw a general comparison, the most relevant Key Performance Indicators (KPIs) have been identified in Table 2.4 for all the protocols analyzed in Sec. 2.5. Here, it is pertinent to note that the significance of each individual KPI depends on the type of WSN application. For example, some applications like fire detection may rate latency as the most critical KPI as compared to energy utilization. Similarly, fairness may be the first choice to consider in some applications with bandwidth constrained wireless links. Hence, the choice of optimization for certain KPIs is challenging and is a matter of tradeoff between most critical KPIs based on the underlying application.

According to the literature review presented so far, fairness is one of the primary KPI (mentioned in Table 2.4) in EH-WSNs. In fact, it is still challenging in WSNs to ensure a fair share of the total bandwidth of the system to the different nodes in order to pursue load balancing and extend network lifetime. Secondly, certain applications in WSNs may be required to achieve guaranteed data delivery due to application critical data frames and it may not always be possible for EH-WSNs because of the non-availability of an active sending node due to its duty-cycle expiry hence it would impose a new design goal. A well-designed transport protocol is also one of the challenging design consideration to regulate the data flow irrespective of the location of the node within the network.

Most of the protocols analyzed in Section 2.5 were proposed to optimize QoS while exploiting the presence of renewable energy. Hence, the mere focus of these protocols was to target the KPIs like throughput and delay optimization instead of energy saving operations and they have been quite successful to improve throughput of the system except [156]. Similarly, most of them are suitable for the delay critical applications except [151, 155, 162] that incur relatively higher delays as compared to their counterparts as shown in Table 2.4.

Energy and data buffers on individual nodes are assumed to be of infinite capacity for the sake of simplicity while designing energy harvesting systems. Similarly, the initial channel conditions are assumed to be of perfect synchronization for simpler experimental set-ups. Furthermore, the only energy consumption source in most of the harvesting models discussed in [164] is assumed to be data transmission, ignoring all other energy consuming processes. This kind of assumptions are unrealistic while modeling energy harvesting systems and future works should consider these lacks while modeling the energy harvesting environments.

Despite being most significant and desperately needed design consideration, only MAC protocol is not enough for a desired performance level in EH-WSNs. Routing protocols are also consideration candidate as in multi-hop WSNs, it is difficult to predict the waking time of the next possible hop for a communication. It may prove to be an even worse scenario if the next hop has depleted the whole energy during the last cycle. Consequently, it would lose the time stamp for the next wake-up and only SyWiM [157] employs mechanism to resynchronize the time stamp. Hence, it would no more be a good choice to wait an unlimited amount of time for that neighbor to be woken back for all other protocols mentioned in Table 2.4. Broadcasting and opportunistic forwarding may then be useful approaches to be adopted with a mechanism to cope the problem of receiving duplicate frames if multiple neighbors are active and ready for reception so that the harvested energy is not wasted. On the other hand, when there are not enough nodes woken-up to serve as a next hop, then delay-tolerant network (DTN) techniques [165] may prove to be useful to play their parts effectively to forward the data to the best possible hop towards destination.

In a typical MAC protocol, bulk of proposals have already been formulated [11-24] for conventional WSNs to achieve longer battery life. It is inevitable for EH-WSN based MAC design to first highlight the possible source of energy wastage (including different energy leaks depending on harvesting technology) and then deduce new mechanisms to efficiently utilize the energy at hand (e.g. seamless synchrony of sleep and wake-up schedules). It is to note that contention-based CSMA/CA has been prominently chosen as basic approach for many MAC protocols customized for EH-WSNs in [145]-[148],[151]-[163] because of its simple, yet comprehensive mechanism for traditional WSNs with the addition to one or multiple techniques presented in Table 2.3. Moreover, another important study is presented in [160, 166] depicting the effectiveness of unslotted CSMA-CA against the slotted one where most of the energy is consumed in slot synchronization.

Almost all the protocols customized for EH-WSNs (discussed thoroughly in section 2.5) refer to a single harvesting technology (e.g., solar, wind or vibrational) because of the unique complexities and trade-offs involved in each technology. Therefore, energy model for each harvesting technology is protocol specific and is different because of different time and environment. Hence, there is not even a single protocol available to perform well with multiple (or even more than one) harvesting technologies.

Validation method is another important aspect that clearly advocates the superiority of one type of protocol over another. Table 2.4 highlights the validation method used for each of the protocols discussed in [145]-[148],[151]-[163] and all of them have been compared against a single or multiple traditional (non-energy harvesting) MAC protocol which does not clearly argue the legitimacy of the evaluation procedure. For an accurate simulation setup to evaluate MAC protocols in EH-WSNs, it is significant to establish a common simulation framework and compare each special MAC protocol against similar other protocols for EH-WSN employing this framework. For example, precise energy model can be implemented and incorporated to a network simulator to evaluate these special protocols for EH-WSN that may exhibit more logical evaluation characteristics for this class of protocols.

Table 2.3: Summary of the MAC protocol techniques customized for EH-WSNs

Technique	**Description**	**Protocol**
Duty-Cycle Adjustment	Adjusting the duty cycle of the nodes based on their energy levels.	• RF-AASP [147] • AH-MAC [148] • ODMAC [152] • LEB-MAC [153] • ERI-MAC [154] • QAEE-MAC [155] • SyWiM [157] • SEHEE-MAC [162] • RF-MAC [163]

Contention Probability Adjustment	Adjusting the Probability of Packet Transmission based on the energy harvesting rates and/or the number of active nodes.	• Prob. Polling SH [145] • MTPP [146] • Prob. Polling MH [151]
Load Balancing	Distributing the load among nodes based on their energy levels	• AH-MAC [148] • ODMAC [152] • LEB-MAC [153]
Energy-aware Deep Sleeping	Letting the low-energy devices go to deep sleep so they can harvest enough energy for future transmission.	• ED-MAC [156] • DeepSleep [159] • SEHEE-MAC [162]
Contention Reduction	Forcing some devices going to sleep and leave the contention.	• RF-AASP [147] • ERI-MAC [154] • ED-MAC [156] • DeepSleep [159] • EL-MAC [161]
Differentiated Contention Window	Assigning different contention windows to different nodes to prioritize some of them over the others.	• RF-AASP [147] • ERI-MAC [154] • QAEE-MAC [155] • DeepSleep [159] • EL-MAC [161] • RF-MAC [163]

Wake-up time Awareness	Incorporating the next wake-up schedule in the beacon to inform potential senders about when the beacon transmission will take place.	• LEB-MAC [153] • QAEE-MAC [155] • SyWiM [157]

Moreover, most of energy harvesting MAC protocols are evaluated based on simulation setups. There may be a possibility to compromise on several unrealistic assumptions in simulation methods that can be avoided by employing real test-beds. Devising a mechanism for practical implementation of these protocols on the real test-beds can be a challenging task. There may be several open issues (e.g., resource allocation and management) while practically implementing the set of protocols on the actual sensor hardware. Therefore, practical implementation and testing of more energy harvesting MAC protocols would significantly influence the performance metrics.

There are separate MAC protocols for special types of energy harvesting sensor network applications (e.g., Body Area Networks [167], Multimedia Sensor Networks [168], Underwater Sensor Networks [169], and Cognitive Radio Sensor Networks [170]) deserving special attention. MAC protocols for all these applications intend to achieve different design goals. Therefore, no single energy harvesting MAC protocol can serve more than one type of special applications because of diverse nature of application scenarios. It evolves the need for a special MAC protocol intended to serve each of the applications of sensor networks with respect to energy harvesting constraints. There exists an opportunity to study MAC protocols targeting special applications of wireless sensor networks keeping in view the design implications of harvesting systems.

Majority of the protocols proposed for EH-WSNs employ duty-cycle adjustment and differentiated contention window schemes with some of them focusing on contention reduction method. These techniques are effective for a MAC protocol aiming to achieve low energy consumption but, on the other hand, more shrinking the duty-cycle and frequent switching between active and sleep modes may also severely influence the performance level of individual nodes. Hence, there exists a thin line between low energy utilization and optimum performance level that should be taken care while designing MAC for EH-WSNs.

Table 2.4: Comparison of performance level of protocols based on important performance indicators

Protocol	**Throughput**	**Latency**	**Scalability**	**Fairness**	**Energy Utilization**	**S/Multihop**	**Validation Method**
Prob. Poll.-SH [145]	High	Moderate	Moderate	High	High	SH	Analyt. Model
MTPP [146]	High	Low	Moderate	Moderate	High	MH	Real Testbeds
RF-AASP [147]	High	Moderate	Low	High	Moderate	SH	Analyt. Model+Sim.
AH-MAC [148]	High	Moderate	Moderate	High	Low	MH	NS-2 Sim.
Prob. Poll.-MH [151]	High	High	High	High	Low	MH	QualNet Sim.
ODMAC [152]	Moderate	Low	Low	Moderate	Moderate	MH	OPNET Sim.
LEB-MAC [153]	Moderate	Low	Low	Moderate	Moderate	MH	Qualnet Sim.
ERI-MAC [154]	High	Low	High	Moderate	Moderate	MH	NS-2 Sim
QAEE-MAC [155]	High	High	Moderate	High	High	SH	Analyt. Model+Sim.
ED-MAC [156]	Low	Low	Low	High	Moderate	SH	NS-2 Sim.
SyWiM [157]	High	Low	Moderate	High	Low	MH	Testbeds+Sim.
DeepSleep [159]	High‘	Moderate	High	High	Low	SH	NS-2 Sim.
EL-MAC [161]	High	Moderate	Moderate	Low	Low	SH	Analyt. Model
SEHEE-MAC [162]	Moderate	High	Moderate	High	Low	SH	Analyt. Model+Testbeds
RF-MAC [163]	High	Low	Moderate	High	Moderate	SH	Testbeds+Sim.

The present can be seen as the era of transition from "Internet of People" to "Internet of Things" (IoT) and this evolution is supposed to be on its peak until 2020 when there may be 50 billion objects connected to the internet according to a report published by CISCO [171]. In addition to their significance as popular standalone networks, WSNs are supposed to be an integral part of ongoing wave of IoT to make them suitable for a range of M2M applications [172]. Compatibility of these MAC protocols for IoT deployments is another challenge. Among the analyzed protocols customized for EH-WSNs, some of them (e.g., [154, 159]) can also be considered for a bulk of future IoT use-cases unless they offer scalability for large scale deployments along with low energy utilization. They can be studied further for their deployments towards energy harvesting-IoT networks.

2.7 Summary

Preserving couple of decades of rich history, Wireless Sensor Networks (WSNs) do still exist among the top niche of most widely deployed wireless technologies of the age because of their unmatchable characteristics in comparison to other counterparts. The emergence of energy scavenging mechanisms gave birth to a variety of new horizons of WSNs enabling them to be deployed for a huge number of energy critical scenarios and applications. This promising combination led the research towards a new set of challenges and trade-offs to be compromised for achieving each design goal (e.g., either longer life time or better performance). This chapter presented a comprehensive review on the current state-of-the-art of this incredible combination keeping in view a set of limitations towards general design considerations.

We first discussed the latest research trends towards energy harvesting area covering various energy scavenging technologies widely used for this combination, energy harvesting architecture, and possible design alternatives significant to this combination. We then elaborated the need for special MAC protocols for EH-WSN. Eventually, we analyzed a range of special MAC protocols presented in the literature for EH-WSN along with their pros and cons of this combination towards achieving an optimal design.

Optimum energy utilization is still one of the fundamental goals of EH-WSN because of the difference between harvesting and consumption rate. It is worth mentioning that only few of the proposed MAC protocols for EH-WSN exhibit efficient energy utilization in true sense as shown in Table 2.4. Furthermore, most of the protocols proposed in this area do not seem to be focusing on minimizing the energy utilization when striving to achieve other performance metrics (e.g., throughput). Most of them do not even evaluate their performance in terms of energy utilization. Furthermore, QoS achievement has also been challenging for this class of protocols. Most of the protocols targeting QoS parameters still suffer with respect to other criteria (such as, end-to-end delay and energy utilization).

Moreover, performance evaluation of these protocols through the widespread implementation on real hardware is seriously lacking and there exists a need to evolve more energy harvesting WSN systems employing MAC protocols on top of them for the real-time performance evaluation.

We argue that there are several strongly-coupled factors to be considered while talking about an optimal MAC design for the EH-WSNs and considering only a single set of limitations for each side (e.g., either WSNs or Energy Harvesting) is never enough towards achieving a satisfactory performance level. This study was aimed at providing a clear roadmap for new researchers to step ahead in design considerations and challenges of this area.

3

A Feasibility Analysis on Cable-less Deployments fed by Renewable Energy

The discussion carried out in Chapter 2 highlighted a range of MAC protocols designed for energy harvesting sensor nodes employed in a variety of applications. Clearly, the Wireless Sensor Networks (WSN) are not the only candidate to consider for the provision of IoT services aligned with energy harvesting and optimal energy utilization requirements in IoT infrastructures. There are a plenty of recently developed technologies and networking protocols that are deemed appropriate to be supported by energy harvesting systems in addition to sensor networks when it comes to large scale IoT deployments. Featured with the extremely low power consumption and long radio coverage, Low Power-Wide Area Network (LP-WAN) paradigm has recently amid a storm of hype and they are being considered as the most feasible option for a plethora of environmental and industrial monitoring applications, but shorter battery life of end-devices appears to be another bottleneck in this kind of IoT use-cases. This chapter throws light on the cable-less (LoRaWAN) gateway deployments in the presence of renewable energy when employing different wireless technologies at a backhaul.

In recent years, LP-WAN gained momentum thanks to their inherent capabilities to support IoT services with broad geographical coverage. Among them, the Long Range Wide Area Network standard, recently promoted by the $LoRa^{TM}$ Alliance, is emerging as one of the most promising solution capable to provide a radio coverage up to tens of kilometers with very low data rates, while working in the unlicensed sub-GHz band.

This chapter focuses on LoRaWAN and sheds some light on the feasibility of fully cable-less Internet of Things deployments, where dual-radio gateways are fed by a photovoltaic plant and equipped with a wireless backhaul. As a first step, the power needs of a dual-radio gateway, serving a mix of realistic Machine-to-Machine applications and leveraging different combinations of front-end chipsets and backhaul wireless technologies, are investigated. Then, the achieved results are properly employed to size the photovoltaic plant, as well as to estimate its installation costs and land acquisition. Finally, cost-saving and carbon footprints analysis is presented to demonstrate the socio-economic benefits arising out of these cable-less deployments for Long Range Wide Area Networks. The conducted study clearly exhibits that network operators can achieve their break-even point during the early stages after the deployment, while adopting environment-friendly approaches because of carbon emission savings achieved by renewable energy.

3.1 Significance of Cable-less LoRaWAN Deployments

As worldwide recognized, conventional LoRaWAN gateways are assumed to have a wired (IP based) connectivity mechanism with the backhaul network. Certainly, a wired backhaul provides a very high capacity. But, it also incurs wiring costs, hinders on-the-fly deployments, and limits network expansion. To circumvent these limitations, the work presented herein proposes a feasibility study that analyzes pros and cons of fully cable-less LoRaWAN gateways, fed by Renewable Energy Sources (RES), and leveraging a wireless backhaul to interact with cloud/network servers and remote applications.

In more details, the following fourfold contributions are achieved in this work. First, the power demand of a cable-less LoRaWAN gateway equipped with a dual radio interface is estimated by taking into account the throughput achievable within LoRaWAN front-end, the energy consumptions of real LoRaWAN gateways currently available in the marketplace, and energy models theorized for different wireless backhaul technologies. Second, power and storage ratings of a Photovoltaic (PV) plant capable to feed a cable-less LoRaWAN gateway, as well as the land occupation of the plant itself, are calculated by properly considering a realistic deployment in the south of Italy.

Third, OPEX and CAPEX for both conventional grid-powered and proposed cable-less LoRaWAN gateways are also estimated and a detailed cost saving is presented to highlight the economic benefits for the network operators. The conducted analysis clearly demonstrates that the network operators can achieve their break-even soon after the deployment of the proposed cable-less architecture. Lastly, an analysis on the carbon emission is presented to spell out the impact of this approach on the environment. Results demonstrate how the proposed model is capable to guarantee an annual carbon emission savings up to 56kg per gateway, when compared against conventional grid-powered infrastructures.

To summarize, the proposed LoRaWAN architecture based on a wireless backhaul and RES emerges as a flexible, cost-effective, and environment-friendly solution. It is an extremely encouraging factor that makes it economically viable for the network operators to consider this approach in terms of return on investment. It is important to remark that LoRaWAN is still undergoing an evolutionary phase. For instance, industrial and scientific communities are currently investigating several challenges related to energy optimization and harvesting in long range networks, different modeling techniques for LoRa, as well as evaluating the performance and the limitations of the LoRa technology (see contributions presented in [173]-[71], and the quick overview of the state-of-the-art discussed in Section 3.2).

The rest of this chapter is organized as follows: recent research trends in the realm of LoRa technology are covered in Section 3.2. Section 3.3 presents the envisaged system model that uses LoRaWAN at the front-end and different wireless technologies at the backhaul. Section 3.4 illustrates the aggregate M2M traffic model for different application scenarios, and estimates the overall power consumption of the proposed cable-less LoRaWAN gateway. The appropriate sizing of PV plant for proposed cable-less LoRa gateway is discussed in Section 3.5, while a detailed feasibility analysis comprising cost and socio-economic benefits is presented in Section 3.6. Finally, concluding remarks and future research activities are presented in Section 3.7.

3.2 Current Research Trends

Several works [173]-[71] recently addressed different issues related to the core LoRaWAN mechanism (discussed throughout this section). In summary, the broad topics of inter-

Table 3.1: A comparison of proposed cable-less LoRa gateway approach with currently available literature

Literature	**Energy harvesting/optimization**	**Modeling**	**Performance evaluation/limitations**	**Cable-less LoRa gateways**
[173]-[175]	✓	x	x	x
[54, 176]	x	x	✓	x
[51, 178]	x	✓	✓	x
[71, 177]	x	x	✓	x
Proposed approach	It extends other solutions targeting these goals by offering cable-less deployments			✓

est include (1) energy optimization and harvesting in long range networks, (2) different modeling techniques for LoRa and, (3) evaluation of several performance metrics (like capacity, scalability, and radio coverage).

In more details, a multi-sensing platform has been proposed by [173] that strives to achieve energy sustainability by employing multiple techniques (i.e. energy harvesting and ultra low-power wake-up radio) for the LoRa based end-devices when deployed in the continuous listening scenarios. Similarly, [174] come up with a circuit capable to handle and switch between multiple harvesting techniques to feed a LoRa end-device to claim improved device autonomy and Quality of Service. Another similar approach has been presented by [175] introducing the floating device integrating energy harvesting and communication system together to achieve longer battery life of LoRa nodes especially in the very long-range communication. A stochastic geometry framework on the performance and scalability of single gateway based LoRa network is presented in [176] which argues about the exponential drop of coverage probability with growing number of end-nodes. An experimental analysis on the coverage of LoRaWAN is conducted in [51]. The authors use maximum transmit power and SF to evidently observe the communication range as 15 km and 30 km for the test-beds located on the ground and water, respectively. The authors also present the channel attenuation model based on the experimental data set to estimate the path loss. The same authors have drawn performance metrics for LoRaWAN end-nodes in [54] and illustrate that a single LoRaWAN cell can support several millions of end-nodes. They conclude that the capacity of uplink LoRaWAN channel is highly dependent on the distance from the gateway. Similarly, the indoor and outdoor performance of LoRaWAN physical layer has been analyzed in [177] which demonstrates that LoRaWAN may be a reliable link for future remote sensing applications. [178] propose a Markov chain model for on-the-air activation (network join procedure) and derive expected delay and energy requirement to join an existing network. Lastly, a survey [71] on the limitations of LoRaWAN with massive M2M traffic declares channel access as the most crucial component and reveals that an accurate interference-aware performance analysis is needed in these conditions.

To the best of our knowledge, all the proposals available in the literature so far (summarized in Table 3.1), leverage a wired LoRaWAN backhaul with grid-powered gateway solutions. This work is not only adaptable and fits well to target several LoRa use-cases available in the current literature, but it also exploits the potential of different wireless technologies employable as the backhaul of LoRaWAN architecture, evaluates the power demand of proposed system when considering wireless backhauls, and proposes an energy harvesting solution in line with the evaluated power demand of dual radio gateways. It further presents statistical analysis on the feasibility of possible wireless backhaul options in terms of costs, deployment, expansion flexibility, and environment-friendliness.

3.3 System model

The LoRaWAN system envisaged in this contribution pursues a completely cable-less architecture, as illustrated in Figure 3.1. Both the front-end and the backhaul communication links are wireless: the LoRa technology is used for the front-end and different wireless technologies may be used to connect the LoRAWAN gateway to the rest of the network. In addition, LoRaWAN gateways are fed by some RES. Thus, energy sustainability represents the key challenge to face in the proposed architecture.

Each kind of RES has its own pros and cons, depending on the type of application and environmental constraints. Nevertheless, employing the photovoltaic plant might be a suitable idea to power up the gateways. Such an approach has already been chosen for other technologies in cellular architectures where low power base stations in micro and femtocells are fed by solar plants [179]. This way, in fact, it is possible

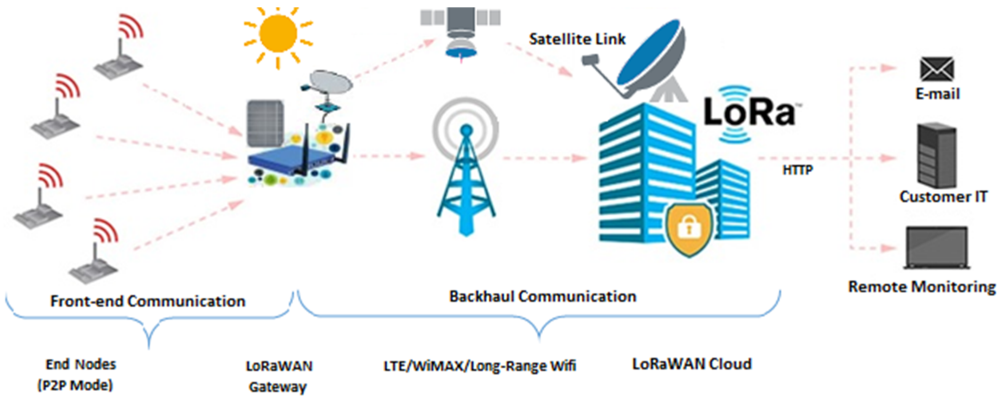


Figure 3.1: Proposed energy harvesting cable-less LoRaWAN architecture supporting multiple wireless backhauls

to reach out a suitable trade-off between the power requirements of the LoRa gateway and the harvesting capacity of the PV plant. Accordingly, the present contribution focuses on cable-less LoRaWAN gateways, equipped with PV plants that are capable of satisfying the power demand of both the front-end communication interface (i.e., the LoRa technology) and the chosen backhaul wireless technologies.

As demonstrated in [179], the resulting energy harvesting architecture would be able to provide flexible architecture, affordable CAPEX, reduced OPEX, and minimized carbon emission. This kind of solution is particularly useful in the use-cases where: (i) the direct grid connectivity is not feasible because of odd installation spot; (ii) the grid connectivity limits the performance (e.g., in terms of achieving optimum radio coverage) of LoRa gateways; and/or (iii) the service providers are intended to cut-down the operating costs. These benefits would not only enable the existing private and public LoRaWAN infrastructures to upgrade themselves, but it would also be able to support new LoRaWAN business use-cases, including:

- **Low power network operations:** one of the unique characteristics of LoRaWAN networks is their operations in the license-free spectrum with certain duty-cycle and maximum-power constraints. The proposed architecture might help network operators to effectively install and operate their gateways while functioning in low power conditions.
- **Coverage and capacity enhancements:** by employing cable-less gateways to the existing LoRaWAN networks, it would enable network operators to quickly

initiate network expansion process yielding improved coverage and capacity of the network in a cost-effective way.

- **Rapid expansion:** the notion of cable-less gateway (employing a wireless backhaul to connect to the core network) would enable existing and new network operators to flexibly install their gateways with minimal costs in urgent situations. It may particularly be feasible in rural areas and developing countries.

- **Lower deployment costs and time to market:** grabbing the possibility of multi-backhaul capabilities, it would be handy for service providers to come up with the speedy deployment of LoRa networks by utilizing many of the existing wireless technologies already deployed in the potential areas. This is far better than the installation from the scratch.

3.3.1 An overview of the different stages of the procedure

Figure 3.2: A big picture of the procedure adopted for proposed cable-less LoRa deployments

Figure 3.2 provides an overview of the various stages involved towards accomplishing a cable-less LoRa gateway. As an initial step, application throughput is calculated for a range of M2M applications that serves an input to further compute the optimal number of end-nodes to be served by a single LoRa gateway. The power consumption is then evaluated as a second step taking into account the consideration of different LoRa vendors and different backhaul technologies based on the aggregated traffic calculated in step 1. Once the power consumption is known for different combinations of front-end and backhaul options, we can move to the sizing phase in step 3 where power rating of a PV plant is calculated. As a step 4, we evaluate the storage requirements to support uninterrupted operation also in the bad weather conditions when the PV plant generation is absent. The appropriate storage ratings are calculated in step 5 to accommodate the ample amount of energy required to support sustainable gateway operation. Lastly, cost and carbon footprints savings calculations are executed as step 6 where a detailed analysis is presented for the network operators with respect to CAPEX, OPEX and break-even points achievable through different front-end and backhaul combinations.

3.3.2 Assumptions and constraints

There are a number of assumptions related to each phase of the procedure presented in Figure 3.2.

As a part of *step 1*, a range of M2M applications are assumed based on the low, middle and high throughput intensive applications to evaluate the extreme traffic requirement and to justify the choice of backhaul technology for various IoT use-cases. Secondly, the evaluation of number of optimal end-nodes served by a single LoRa gateway assumes a pure aloha based channel access, which only considers 3 and 6 LoRa channel configurations. *Step 2* assumes an average power consumption reading for all the combinations of front-end and backhaul technologies. While evaluating front-end power consumptions, a slight variation in the consumption reading due to different hardware chipset is negligible. Moreover, different assumptions related to the power consumption of each backhaul technology are presented in detail in Section 3.4.2. *Step 3* presumes weather conditions of a specific region while calculating the power ratings for PV plants. The related outcomes are used when evaluating power requirements for a weak of bad weather conditions in *step 4*. Hence, the number of days with bad weather

Algorithm 1 /2: The pseudo-code for the detailed procedure

```
procedure DIFFERENT STAGES OF THE PROCEDURE (CONTINUE...)
Step 1: Calculate the aggregate Traffic on a gateway
    $\Psi \leftarrow$ available spreading factors from 7 to 12
    $n_j \leftarrow$ max no. of end-nodes supported by a SF
    $c \leftarrow$ the number of LoRa channels
        Calculate optimal number of end-nodes, $O_n$ using Eq. (3.1)
    $S_{app} \leftarrow$ average packet size
    $R_{app} \leftarrow$ average tranmission rate
        Using $O_n$, calculate the achievable throughput,$T_{app}$ using Eq. (3.2)
Step 2: Estimate the overall power consumption, $P_{tot}$
    $P_{FE} \leftarrow$ avg. power consumption of LoRa front-end
    $P_{BH} \leftarrow$ avg. power consumption of backhaul tech.
    for <Frontend LoRa GW Vendor> do
        for <Backhaul Technology> do
            Calculate total power     consumption,$P_{tot}$ using Eq. (3.3)
        end for
    end for
Step 3: Calculate the power rating of a PV plant, $P_{PV\_rating}$
$H_{ins} \leftarrow$ average insolation period
$H_{year} \leftarrow$ total number of hours in a year
$P_{tot} \leftarrow$ total power consumption calculated in step 2
    for <Frontend LoRa GW Vendor> do
        for <Backhaul Technology> do
            Calculate power rating, $P_{PV\_rating}$ for all $P_{tot}$ in Step 2 using Eq. (3.5)
        end for
    end for
Step 4: Calculate energy demand for a weak of bad weather conditions
$N_{BW} \leftarrow$ the number of days of bad weather
Energy demand during bad weather conditions, $E_{BW} = N_{BW} \cdot 24h \cdot P_{tot}$
end procedure
```

Algorithm 2 /2: The pseudo-code for the detailed procedure

```
procedure DIFFERENT STAGES OF THE PROCEDURE (REMAINING)
Step 5: Estimate the storage rating, $P_{storage\_rating}$
$\eta_{batt.} \leftarrow$ percentage of battery efficiency
$T_{discharge} \leftarrow$ battery discharge time
    for <Frontend LoRa GW Vendor> do
        for <Backhaul Technology> do
            Calculate storage rating, $P_{storage\_rating}$ for all $P_{tot}$ in Step 2
             using Eq. (3.7)
        end for
    end for
Step 6: Estimate the cost and carbon footprints savings
    for <Frontend LoRa GW Vendor> do
        for <Backhaul Technology> do
            Cost Saving (CS) is calculated as a function of $C^{Grid}_{CAPEX}$
 using Eq. (3.8) and Carbon footprint saving is evaluated using Eq.
 (4.17)
        end for
    end for
end procedure
```

conditions would vary with respect to certain regions. The lithium-ion battery of 90% efficiency and 4h discharge time is assumed while evaluating the storage rating on *step 5*. Furthermore, *step 6* assumes 10 years of lifetime for cable-less LoRa architecture. It further assumes to neglect the costs involved in the land acquisition while calculating the cost savings for network operators.

The proposed work is carried out considering the deployments in the south of Italy based on the local weather conditions. Therefore, geographical location may be seen as one of the main constraints where the proposed approach needs to be adapted as the results may undergo abrupt variations in different regions because of the variable insolation period, and number of days with precipitation, of various regions (See Section 3.5 for the details).

3.4 Estimating the power consumption

Starting from the considerations drawn in the Section 3.3, this Section aims at evaluating power demand of a cable-less LoRaWAN gateway, based on application and communication settings. Obtained results will be used later for sizing the PV plant (see Section 3.5) and performing cost-saving and carbon footprint analysis (see Section 3.6).

3.4.1 Aggregate Traffic Model for M2M Applications

Typical M2M application scenarios include Roadway Signs, Traffic Lights/Sensors, House Appliances, Credit Machine in a shop, and Home Security [54, 180]. The aggregate traffic that a LoRaWAN gateway has to manage is estimated by taking into account a range of real IoT applications. It essentially serves the twofold purpose. First, identifying an appropriate backhaul technology for LoRaWAN network architecture that supports the aggregate traffic. Second, evaluating the energy consumption of proposed cable-less gateway in the presence of a wireless backhaul technology.

The LoRaWAN cell is defined as the portion of the LoRaWAN network handled by a single gateway. Let Ψ be the number of available spreading factors, chosen from 7 to 12 as already discussed in Section 1.7.4 of the chapter 1. The number of end-nodes that can successfully be served in a LoRaWAN cell depends on (i) the maximum number of end-nodes supported by every single spreading factor, n_j, with $0 \leq j < \Psi$, (ii) the number of channels, c, and the real number of nodes whose transmissions do not collide over the shared channel. Now, considering the pure ALOHA as the baseline channel access mechanism, it can be assumed that 1/2e of the end-nodes in perfect synchronization can be supported optimally in collision situations within a LoRaWAN cell [54].

Thus, the optimal number of end-nodes supported in a LoRaWAN cell, O_n, can be expressed as [54]:

$$O_n = \frac{1}{2e}\, c \sum_{j=0}^{\Psi} n_j \tag{3.1}$$

In addition, for every single M2M application listed above, the upper bound value of the achievable throughput, T_{app}, can be computed as:

$$T_{app} = \frac{S_{app}}{R_{app}} O_n = \frac{S_{app}}{R_{app}} \frac{1}{2e} c \sum_{j=0}^{\Psi} n_j, \tag{3.2}$$

where S_{app} and R_{app} are the average packet size and the average message transaction time (i.e., the time between two consecutive packets) of a given application, respectively.

Figure 3.3 shows the upper bound value of the achievable throughput against various M2M application scenarios. It is computed by considering configurations with three and six LoRa channels of 125kHz each. Of course, a higher number of channels can accommodate more number of optimal end devices and, hence, yielding higher throughput. Moreover, it is possible to observe the results that, being a low data rate technology, LoRaWAN can still support a bulk of application scenarios for IoT. But, it is pertinent to note that the throughput requirement for most of the M2M application scenarios in LoRaWAN does not go beyond few kilobits per second as shown in Figure 3.3.

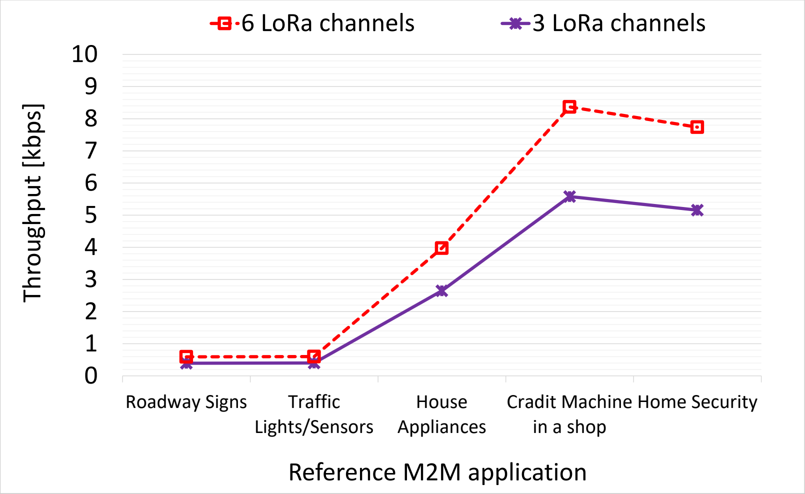


Figure 3.3: Upper bound of the throughput of LoRaWAN against various M2M application Scenarios

3.4.2 Power Consumptions for a cable-less LoRaWAN gateway

The overall power consumption of a cable-less LoRaWAN gateway in dual radio mode, P_{tot}, would be the combination of the power requirements due to front-end, i.e., P_{FE}, and backhaul communications, i.e., P_{BH}:

$$P_{tot} = P_{FE} + P_{BH}. \tag{3.3}$$

Of course, P_{FE} refers to the specific implementation of the LoRa technology. P_{BH}, instead, depends on the wireless technology adopted for the backhaul. Here, It is significant to note that the energy evaluation drawn in this section for both front-end and backhual combinations, represents the overall energy demands to make the devices operational.

Front-end power consumption, P_{FE}

A lot of companies (i.e., Multitech, Microchip, Libelium, Loriot and many others) are providing end-to-end LoRa business solutions for catering the needs of many different enterprises. Their solution kits include LoRa cloud/network servers, gateways and, end-nodes (intended for LoRaWAN applications) with license covering full/partial network support for a contract period. Some of the companies are core manufacturers; while others outsource most of the components for their clients. The average power consumption readings for front-end LoRa communication chipset, along with the lower and upper energy bounds of different LoRa gateways (chosen from Section 1.6.1 of the Chapter 1) available in the market, are mentioned in Table 3.2. The overall power consumption values are calculated based on the information provided within the data sheets of different LoRa gateway vendors[1].

Backhaul power consumption, P_{BH}

For the backhaul, four important and most widely used wireless technologies are considered in this study. They can be employed in combination with LoRaWAN networks

---

[1] Multitech Conduit: `http://www.multitech.net/developer/products/conduit/mtcdt-power-draw`
Embit EMB-Gateway1301: `http://www.embit.eu/wp-content/uploads/EMB-GW1301_20160718.pdf`
Kerlink Wirenet 868: `http://www.kerlink.fr/en/products/lora-iot-station-2/wirnet-station-868`
LoRANK 8: `https://webshop.ideetron.nl/LORANK-8`
Links-lab LoRa: `http://www1.futureelectronics.com/doc/LINK%20LABS/LL-BST-8.pdf`
Lorrier LR2: `https://lorrier.com`

Table 3.2: Power consumption of front-end LoRaWAN gateways offered by different vendors

	P_{FE} **(W)**		
LoRaWAN Gateway Vendors	Min.	Max.	Average
Multitech Conduit	5.69	6.68	**6.18**
Embit EMB-GW1301	5	7.5	**6.25**
Kerlink Wirenet 868	3	15	**9**
LoRANK 8	N/A	N/A	**10**
Links-lab LoRa	10	13	**11.5**
Lorrier LR2	N/A	N/A	**12.44**

where the traffic demands are not higher even in peak traffic scenarios, while offering good performance in terms of coverage, network capacity, and scalability. The selected backhaul technologies that satisfy these requirements include LTE [181], Worldwide Interoperability for Microwave Access (WiMAX) [182], satellite [183], and Long-Range WiFi [184]. Note that all these technologies have widely been adopted for backhaul deployments except Long-Range WiFi which has recently been launched by IEEE 802.11 task group [185].

The energy consumption related to each of these technologies is evaluated by considering a set of assumptions to make its calculation straightforward. It involves many complexities when estimating the partial energy consumption for a single network component while ignoring others that may cause slight variations in value reading. Similarly, power consumption is highly dependent on the underlying hardware chipset and may vary from vendor to vendor.

LTE has already been recognized as a widespread commercialized standard for cellular networks. It is capable to support reasonable bandwidth with fair radio coverage; good enough to be served as backhaul for LoRaWAN networks. In LTE, the amount of power consumed by a mobile terminal is influenced by several components, like base power (minimum power required when the mobile terminal is switched on with modem and transceiver both off), transceiver, modem, and microprocessor consumption with a transceiver variability of ±0.1W. Transceiver and microprocessor introduce the major power consumption when compared to the other components. Also, the energy demand of the transceiver may introduce slight changes when the physical data rate increases. Nevertheless, with reference to the aggregate traffic load available within a LoRaWAN cell, it is possible to safely set the power consumption of an LTE mobile terminal to an upper bound value equal to $5.10W$. Specifically, this value is obtained by subtracting the amount of power needed for screen illumination from the summation of power needed by all other components such as modem, transceiver, and microprocessor [186].

WiMAX has proven itself as a prominent broadband wide area solution for wireless networks. It exploits the advantages of Orthogonal Frequency Division Multiplexing (OFDM) technique yielding long coverage with high data rate support. WiMAX has already been recognized as the strong backhaul technology with multiple front-end access infrastructures. The Customer Premises Equipment (or simply named WiMAX modem) is responsible for relaying the user traffic through the backhaul network in WiMAX. Alvarion BreezeMAX USB 200 Zyxel MAX-200M1 device is considered to estimate the power consumption of Customer Premises Equipment. It is recorded as $5W$ approximately for the mentioned Customer Premises Equipment model while neglecting slight variations possible due to different hardware chipset [187].

Satellite Networks might be another significant candidate that successfully conforms to the requirements drawn by front-end LoRaWAN network. It is capable to provide low data rate support on very long distances with the delays compromisable for many M2M applications. In fact, it may be a promising approach for LoRaWAN to employ satellite networks as a backhaul for covering such a long distance that does not seem achievable with conventional LoRaWAN networks especially in urban areas. European Telecommunications Standards Institute (ETSI) recently published a comprehensive report, i.e., [188], on evaluating the power needs of various components of a satellite broadband network. Specifically, the power consumed by satellite terminal can be evaluated as:

$$P_{BH}^{sat} = T_{full}\, P_{full} + T_{standby}\, P_{standby}, \tag{3.4}$$

where $T_{full}, T_{standby}, P_{full}$, and $P_{standby}$ are the proportions of time spent (duty-cycle) and power consumptions during that time respectively in full and standby activity modes. The satellite terminal consumes $22W$ and $3.14W$ when it works in full and standby activity modes, respectively. This work considers a broadband satellite offering a throughput of $0.5Tbps$, capable of supporting maximum $227,000$ nodes. Considering this fact, it is pertinent to note that 0.1% of total duty-cycle allocated to a single node, should be enough to support the throughput needs reported in Figure 3.3. In this case, the satellite terminal needs to be in full activity mode only for 0.1% of the time and it would remain on standby mode for the rest of 99.9% duty-cycle. Then, by setting the duty-cycle in full activity mode to 0.1%, it is easy to realize that the power consumed by a satellite terminal is equal to $3.16W$ using Eq. (3.4).

Long-Range WiFi (standardized as IEEE 802.11ah) is another emerging backhaul capable technology operated in the sub-GHz band. This technology is intended to specifically target most of the future IoT and M2M scenarios. Despite very recent standardizations, it has already taken many breaths away and is being considered an effective milestone achieved by IEEE task group. It targets a significantly higher radio coverage than its predecessors on the cost of compromising on intermediary data rate; even then enough to serve the needs of many prospective LoRa applications. Hence, it may also be one of the candidates to support backhaul communication in combination with front-end LoRa. Thanks to the notion of Traffic Indication Map and Page Segmentation, extremely low power consumption is one of the major reasons to support Long-Range WiFi. The power consumption of Long-Range WiFi gateway can be approximated not more than $1.35W$ assuming full load and neglecting the slight power variation in circuitry differences [189, 190]. It is important to note that Long-Range WiFi offers significantly lower energy consumption but the radio coverage may vary up to a maximum of $1km$. To conclude, Table 3.3 presents some relevant parameters related to the proposed wireless technologies considered for the LoRaWAN backhaul.

Table 3.3: Important parameters exhibiting backhaul capabilities for wireless technologies

Technology	**Data rate (Mbps)**	**Coverage (Km)**	**Spectrum**	P_{BH} **(W)**
LTE	0.5-28	5-50	Licensed	**5.10**
WiMAX	20-30	6-10	Lic. and Unlic.	**5.00**
Satellite	2.2-10	100-36000	Lic. and Unlic.	**3.16**
Long-Range WiFi	0.65-234	1	Unlicensed	**1.35**

Overall power consumption, P_{tot}

Despite being different with respect to throughput profiles demonstrated in Figure 3.3, the applications (requiring very low data rate) do not significantly influence the total power consumption. Therefore, for the scope of this work, the power profile related to the most energy-consuming application is taken into account. It is also assumed that the LoRa interface of a gateway is always-on, i.e., 24 hours/7 days. Furthermore, it works with its full potential (constantly listening on maximum number of supportable channels using all the LoRaWAN data rate options simultaneously), thus always registering an average power consumption as reported in the latest column of Table 3.2.

In line with these premises, Figure 3.4 shows the resulting power demand against each LoRaWAN gateway vendor when choosing different backhaul technologies discussed above. Obtained results clearly demonstrate how does an LTE-based backhaul cause higher power consumption, which varies from $11.28W$ to $17.5W$ with respect to different LoRa vendors considered in the proposed analysis. At the same time, a WiMAX backhaul also depicts the consumption readings quite similar to LTE. Then, the power consumption of a satellite backhaul becomes moderate. But, it is evident how Long-Range WiFi exhibits the lower power consumption when compared to other backhaul solutions. In particular, its power consumption spans from $7.53W$ to $13.75W$, depending on different LoRa vendors. On the other hand, by focusing the attention on different LoRa vendors, it is possible to observe that, at the time of this writing, Multitech's Conduit provides the most energy-efficient LoRa gateway.

3.5 Sizing the Photovoltaic plant

Sizing the PV plant refers to evaluating the appropriate size of solar modules and storage batteries required to make the proposed cable-less LoRaWAN gateway always operational. It is done by addressing two main considerations. First, the size of a PV plant is evaluated based on power demand of the cable-less LoRaWAN gateway, the standard solar radiations in a specific geographical region, and the efficiency of the solar module based on its material. Second, sizing the batteries (storage rating) depends on the amount of energy required to feed the cable-less LoRaWAN gateway also during the cloudy days. To this end, the same procedure depicted in Algorithm 1 is followed throughout this Section.

As PV plants endure incapability to harvest energy in the absence of sunlight, they must be sized to cater worst-case conditions. In particular, the size of PV plant and storage capacity should appropriately be evaluated to accommodate the energy harvested

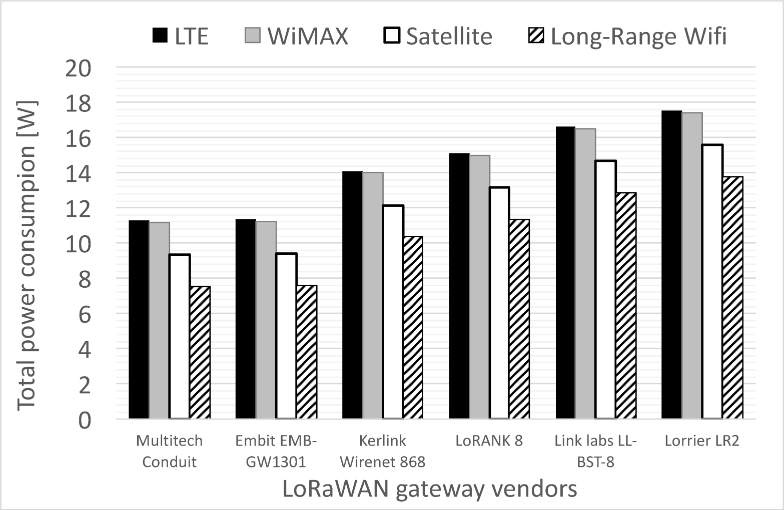


Figure 3.4: Overall power consumption of a cable-less gateway, evaluated against different LoRa vendors and backhaul options

during seven consecutive sunny days of summer. This surplus energy accumulated on the storage can be utilized to filter out the fluctuations of energy availability in cloudy winter days. But, It solely depends on the weather conditions of a particular region. Here, we are considering a PV plant installed in the City of Bari, on the southern part of Italy. Taking into account the meteorological record of this region [191], the number of days with bad weather conditions ranges from two to seven in a month round the year. As a worst case scenario, there may be a possibility of seven consecutive days of bad weather per calendar month in a cloudy winter. Hence, the PV system is designed keeping in view the worst case conditions and is capable enough to compensate the energy demands during this period to make the cable-less LoRa gateways always operational.

3.5.1 Power rating of the PV plant

Starting from the assumption that a cable-less LoRaWAN gateway is always operational, the maximum amount of energy that an individual PV plant has to generate, i.e., P_{PV_rating}, depends upon the three factors:

- the power requirement of a cable-less gateway, i.e., P_{tot}, already evaluated in Section 3.4.2 and also reported in Figure 3.4;
- the total number of hours available within a year, i.e., $H_{year} = 8,760$; and
- the number of hours in a year during which the PV plant is directly exposed to sun's radiations, sometimes known as insolation period, i.e., H_{ins}.

Therefore, P_{PV_rating} can be represented as:

$$P_{PV\_rating} = \frac{P_{tot} \, H_{year}}{H_{ins}}. \tag{3.5}$$

The value of P_{PV_rating} against different LoRa gateway vendors and backhaul wireless technologies is depicted in Figure 3.5. It is evaluated by setting $H_{ins} = 1400$, which represents the average insolation period for the Mediterranean countries (like the southern part of Italy) [192].

3.5, it is possible to observe that P_{PV_rating} varies between $47.12W$ and $109.5W$, depending upon the chosen combinations of front-end chipsets and backhaul solutions. Moreover, as expected from Eq. (3.5), the higher the power requirement of a cable-less gateway, the higher the capability of a suitable PV plant. As already highlighted in Figure 3.4, the Multitech Conduit LoRa chipset, when employing with Long-Range WiFi as a backhaul, exhibits the minimum power requirement. Accordingly, it yields the lower bound of P_{PV_rating}. On the contrary, Lorrier LR2 registers the maximum power consumption when combined with LTE as a backhaul, thus achieving the upper bound of P_{PV_rating}.

3.5.2 Storage rating of the PV plant

Let the *production profile* be the amount of energy harvested, hour by hour, during the day. It is closely coupled with the environment where the plant is installed and its statistics would undergo abrupt variations for different regions. The location and orientation of solar panels is also important and may significantly affect the expected output. For example, an array tilt would significantly affect the output up to 20% as compared to a flat surface. It has been observed that the tilt angle of 20 to 30 degree from the horizontal surface would yield the highest level of output in most of

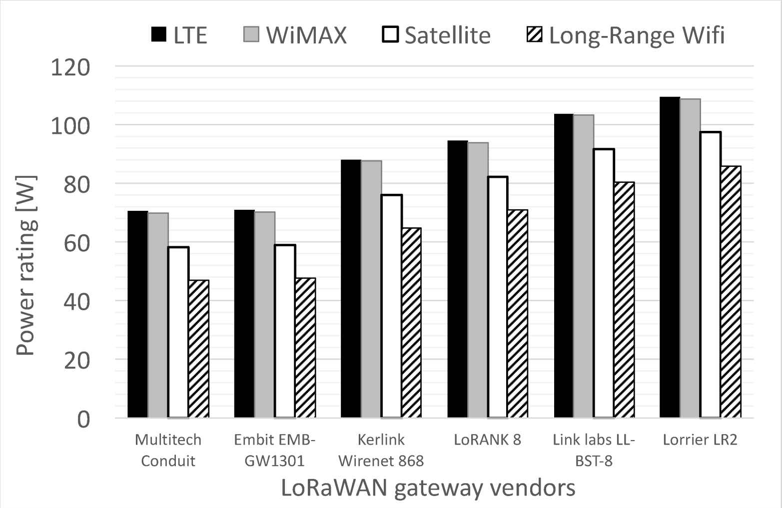


Figure 3.5: Power rating of a PV plant, evaluated against different LoRa gateway vendors and backhaul options

the regions. This affect goes on increasing from south to north regions moving away from the equator [193].

As per the physical constraint, PV plant can only harvest energy during the daylight hours. Therefore, the size of storage device must be properly evaluated in order to accommodate the amount of energy needed for powering a gateway also at night time. In this context, to size the storage device accordingly, it is necessary to evaluate the excessive amount of energy generated by the PV plant during the day, the energy deficiency for the night time, and the amount of excessive energy that is stored in the storage after a full day.

As a first step, let $E_{daylight}$ and E_{night} be the total excessive amount of energy generated by the PV plant after a full day of activity and the energy deficiency of the plant for the night time, respectively. More specifically, $E_{daylight}$ is accumulated in the hours when the production of the PV plant is higher than the power load (as shown in Figure 3.7). On the other hand, E_{night} represents the minimum amount of energy required for the continuous operation at night times when the production profiles are almost reaching zero. By jointly considering power demands of all the considered cable-less

LoRaWAN gateways and the power profile of PV plant properly sized for each combination of front-end and backhaul technologies, $E_{daylight}$ and E_{night} are calculated and reported in Table 3.4. From reported values, it is possible to observe that E_{night} always remains far lesser than $E_{daylight}$. Indeed, $E_{daylight}$ does not only helps compensating the energy demands at night time, but it also excesses an amount consumable during the cloudy days when the consumption profile is higher than production. In line with the previous considerations, the amount of energy that can be accumulated in the storage after a full day of activities (i.e., complete day and night cycle), namely E_{day},can be obtained as:

Table 3.4: Excessive energy generated by the plant and energy deficit at night against different LoRa gateway vendors with multiple backhaul options

Excessive energy generated after a full day [KWh]

Available gateway options	LTE	WiMAX	Satellite	Long-Range WiFi
Multitech Conduit	1.526	1.527	1.551	1.576
Embit EMB-GW1301	1.525	1.526	1.550	1.575
Kerlink Wirenet 868	1.492	1.493	1.515	1.538
LoRANK 8	1.480	1.481	1.503	1.525
Link labs LL-BST-8	1.462	1.463	1.485	1.507
Lorrier LR2	1.451	1.452	1.474	1.496

Energy deficit at night [Wh]

Available gateway options	LTE	WiMAX	Satellite	Long-Range WiFi
Multitech Conduit	117.41	116.29	95.71	76.28
Embit EMB-GW1301	118.20	117.08	96.46	77.03
Kerlink Wirenet 868	151.51	150.29	127.78	106.97
LoRANK 8	163.74	162.52	140.01	118.20
Link labs LL-BST-8	182.09	180.87	158.36	136.22
Lorrier LR2	193.10	191.88	169.37	147.23

$$E_{day} = E_{daylight} - E_{night}. \tag{3.6}$$

The resulting values of E_{day} are depicted in Figure 3.6. Here, it can be observed that up to $1.5kW$ of excessive energy can be accumulated after a full sunny day activity considering the combination of Multitech Conduit and Long-Range WiFi. Similarly, the lower bound of excessive energy accumulated after a clear sunny day is $1.25kW$ in case of Lorrier LR2 with LTE backhaul. The accumulated energy during a sunny week in summer may compensate the energy demands for several cloudy days in winter when the production profile severely deviates in the absence of sunlight.

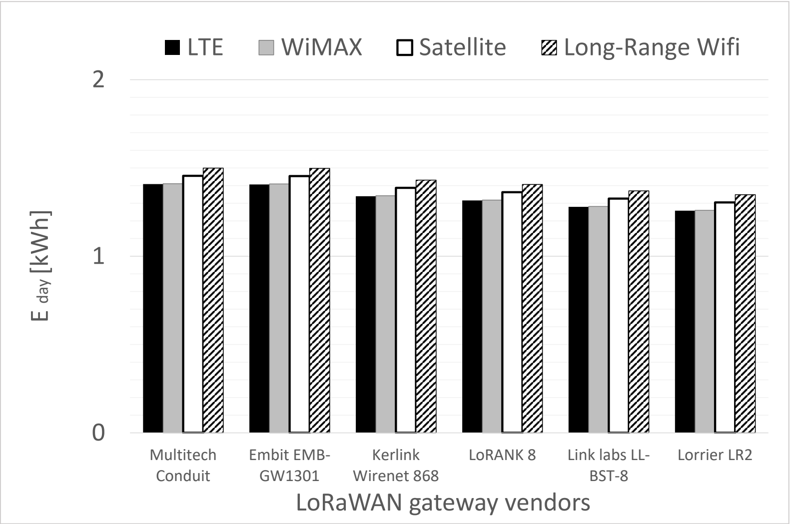


Figure 3.6: Accumulated energy after a full day against different LoRa gateway vendors with multiple backhaul options

Just to provide an example, Figure 3.7 shows the production profile related to a PV plant working on a clear sunny day, as well as dimensioned for a cable-less LoRaWAN gateway that uses the Multitech Conduit chip as the front-end technology and LTE as the backhaul technology. From the Figure, it is possible to observe that production profile varies as a function of the time and reaches a peak value around midday. On the other hand, instead, the power demand, i.e., P_{tot}, remains the same throughout the day for each combination of vendor and chosen backhaul. Here, there is a clear possibility of saving the surplus amount of harvested energy during the daytime that can compensate the power demand at night time, as well as the amount of energy required to feed the cable-less LoRaWAN gateway on cloudy days when the consumption profile is higher than production.

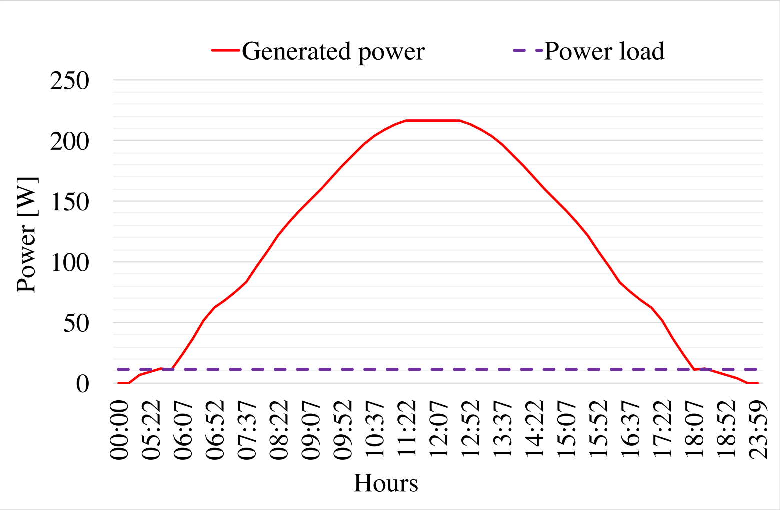


Figure 3.7: Energy production profile of a PV plant against the load on a full summer day of south Italy

It is important to note that the appropriate size of storage rating also depends upon the actual weather conditions of a specific region. As per meteorological record of Bari, a city located in the south of Italy, the average number of days with precipitation, N_{BW}, ranges from two to seven in a calendar month [191]. Hence, the appropriate size of the storage can be obtained by considering an extreme weather condition characterized by seven consecutive days of precipitation(i.e., $N_{BW} = 7$) to support uninterrupted operation round the year. In other words, in order to make a cable-less LoRaWAN gateway operational also in these seven days, the storage must provide an amount of energy equal to $N_{BW} \cdot 24h \cdot P_{tot}$.

Now, let $\eta_{batt.}$ be the efficiency of the storage and $T_{discharge}$ be the total discharge time of the storage, then by assuming $\eta_{batt.} = 90\%$ and $T_{discharge} = 4\ h$ for a lithium-ion battery [179], the storage rating can simply be expressed as:

$$P_{storage\_rating} = \frac{N_{BW} \cdot 24 \cdot P_{tot}}{4 \cdot 0.9}. \tag{3.7}$$

Results are reported in Figure 3.8. Also in this case, it is possible to remark the same considerations: the storage rating increases with the power needs of a cable-less LoRaWAN gateway and the combination of Multitech Conduit chipset along with Long-Range WiFi backhaul is able to register the lowest battery size.

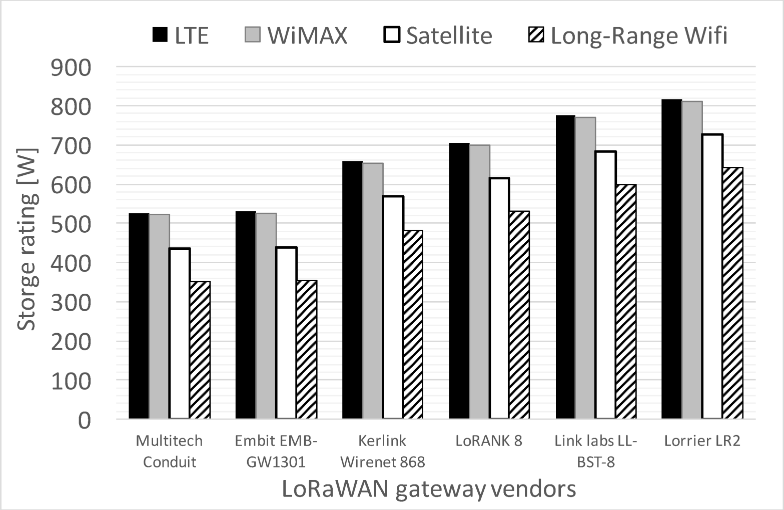


Figure 3.8: Storage rating of a PV plant, evaluated against different LoRa gateway vendors and backhaul options

Furthermore, it should be clear that the storage rating can significantly be affected in case of different charge/discharge cycle. Similarly, considering other types of batteries (e.g. lithium-polymer battery or nickel-cadmium battery) would also affect the efficiency and charge/discharge cycle instead of a lithium-ion battery. Moreover, as per the physical constraint, the efficiency does not remain constant as the battery life goes on.

3.6 Cost-saving and carbon footprint analysis

The aim of this Section is to highlight the socio-economic benefits derived from the deployment of cable-less LoRaWAN gateways.

First of all, the OPEX related to a conventional grid-powered LoRaWAN gateway are evaluated, just to immediately demonstrate that this kind of costs can entirely be avoided when employing the proposed cable-less gateway architecture. Then, installation costs are evaluated for the proposed approach to present an in-depth cost-saving investigation. This analysis considers the costs incurred for solar modules as well as storage batteries while ignoring the common costs (i.e., land acquisition and maintenance costs), that are the same in both conventional and the proposed approaches. The obtained results aim to clarify the conditions when the network operators can reach their break-even point when deploying the proposed approach.

Furthermore, the impact of the proposed approach on the environment is also investigated. The study intends to argue that a substantial amount of carbon emission due to ICT infrastructures can be reduced by employing the proposed energy harvesting approach and tons of carbon emission savings can be achieved annually.

3.6.1 OPEX related to a conventional grid-powered LoRaWAN gateway

Annual OPEX due to energy consumption is the first among overall costs that can be reduced by employing the proposed cable-less gateway architecture for public and private LoRaWAN infrastructure providers. As mentioned in Section 3.4.2, the energy demands for a dual interface cable-less gateway have been evaluated by encompassing the energy consumption of the main functional units of the gateway including dual interface antennas, power amplifier, RF transceivers, modem and, power supply.

Table 3.5 shows the OPEX due to the energy consumption by a single gateway when connected to a power grid. It holds particular importance in case of large-scale deployments where hundreds (in some cases, thousands) of gateways may be deployed. Results demonstrate the annual costs and the costs after 10 years of activity, respectively, in two rightmost columns. In particular, OPEX is computed by considering the average electricity price for Italian industry, that is about 0.2 €/kWh [194].

3.6.2 CAPEX related to a cable-less LoWaWAN gateway

Power and storage ratings of a PV plant significantly influence installation costs. In Italy, the average cost of a lithium-ion battery together with PV plant is around 2,000 €/kW [195]. This value is taken into account for estimating the CAPEX needed to deploy a cable-less LoRaWAN gateway. Obtained results are shown in Figure 3.9. In general, installation costs of a PV plant for a cable-less LoRaWAN gateway ranges from 797 € to 1,852 €. In particular, the lowest costs can be achieved when the combination

Table 3.5: OPEX related to conventional grid-powered LoRaWAN gateways, evaluated against different vendors

LoRaWAN Gateway Vendors	**Yearly power demand [kW/h]**	**Yearly OPEX [€]**	**OPEX over 10 years [€]**
Multitech Conduit	54.13	**10.83**	**108.3**
Embit EMB-GW1301	54.75	**10.95**	**109.5**
Kerlink Wirenet 868	78.84	**15.77**	**157.7**
LoRANK 8	87.6	**16.81**	**168.1**
Links-lab LoRa	100.74	**20.15**	**201.5**
Lorrier LR2	108.97	**21.8**	**218.0**

of Multitech Conduit chip is chosen as a front-end communication interface and the Long-Range WiFi is adopted for the backhaul link.

Here, the highest CAPEX is incurred in case of Lorrier LR2 gateway when employing an LTE or WiMAX backhaul. The CAPEX using these backhaul technologies is almost the same with all the gateway vendors ranging from €1.2K to €1.85K. Similarly, the CAPEX for Multitech Conduit and Embit EMB-GW1301 are almost the same for all the backhaul technologies ranging from €0.8K to €1.2K. On the other hand, the minimum CAPEX needed is reported around €790 in case of Multitech Conduit gateway when employing Long-Range WiFi as the backhaul.

It is pertinent to note that the CAPEX is calculated for a PV system aiming to store ample energy to ensure an uninterrupted operation of LoRaWAN gateway keeping in view the seven consecutive days of bad weather conditions. Of course, it can significantly be reduced for shorter periods. In addition, this CAPEX can also be reduced by buying solar panels and battery cells of lower quality.

3.6.3 Cost-saving analysis

From the network operator's point of view, cost-saving is one of the most significant metrics to calculate for evaluating the usefulness of the proposed architecture. Indeed, the analysis presented herein aims at demonstrating a set of conditions according to which the deployment of cable-less LoRaWAN architecture represents a suitable solution from the economic perspective. To this end, it is assumed that the lifetime of the

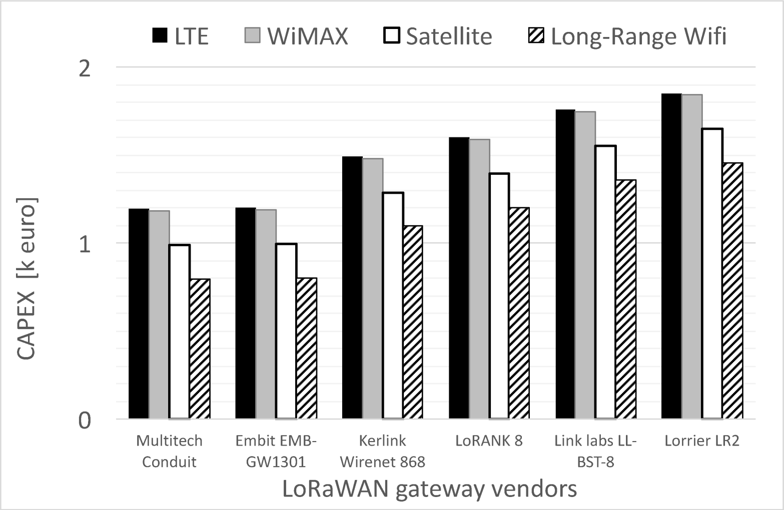


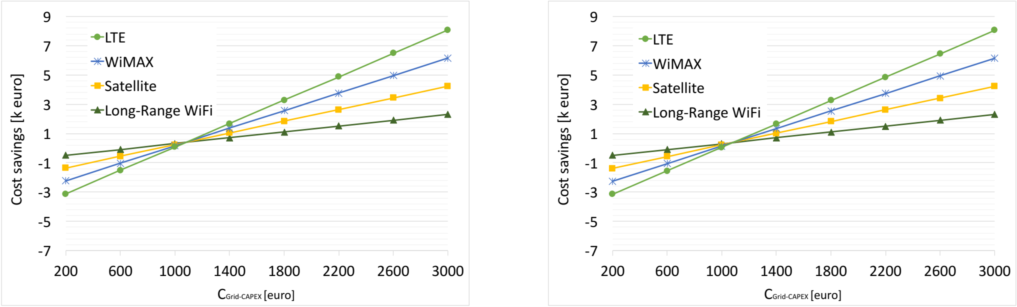
Figure 3.9: CAPEX related to a PV plant feeding a cable-less LoRaWAN gateway, evaluated against different LoRa gateway vendors and backhaul options

LoRaWAN architecture is set to 10 years.

Let C^{Grid}_{CAPEX}, C^{Grid}_{OPEX}, C^{PV}_{CAPEX}, and C^{PV}_{land} be the capital costs required for setting up a grid connectivity, the operational costs related to the conventional grid-based LoRaWAN deployment and estimated over the period of 10 years, the capital cost incurred for the deployment of the proposed architecture (as reported in Figure 3.9), and the operational cost related to the land acquisition of a PV plant estimated over the period of 10 years, respectively. Thus, the cost-saving after the reference period of 10 years, i.e, CS, can be estimated as:

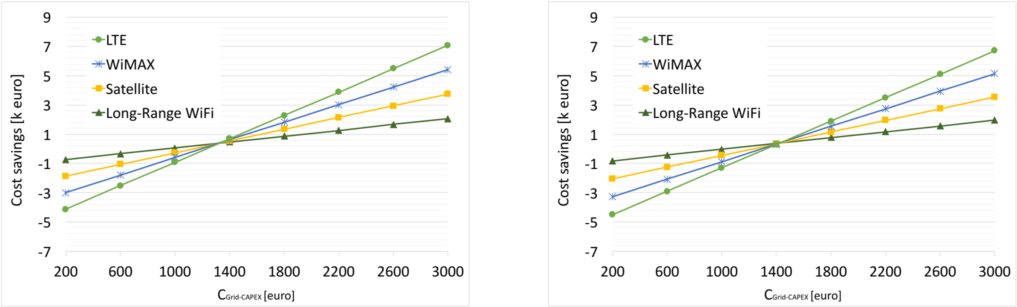
$$CS = C^{Grid}_{CAPEX} + C^{Grid}_{OPEX} - C^{PV}_{CAPEX} - C^{PV}_{land}. \tag{3.8}$$

All the common costs (i.e. actual investment in each gateway, site acquisition, and maintenance costs) have not been taken into account for this analysis, as they are the same in both the cases. On the one hand, C^{Grid}_{OPEX} and C^{PV}_{CAPEX} are reported in Table 3.5 and Figure 3.9, respectively. On another hand, instead, C^{PV}_{land} can be evaluated by taking into account the land needed to acquire for the installation of PV plant.



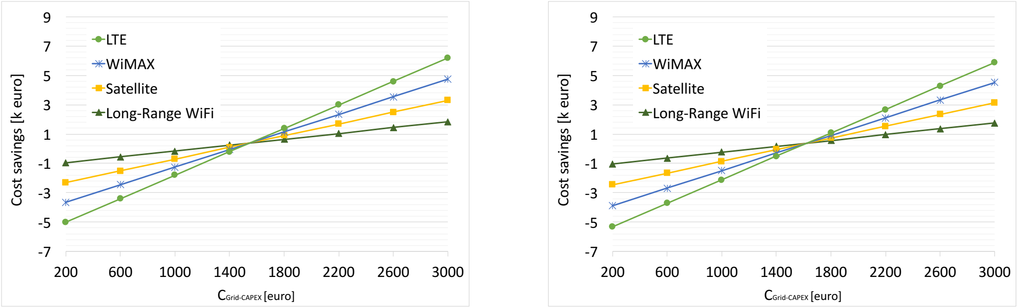
(a) Multitech Conduit

(b) Embit EMB-GW1301



(c) Kerlink Wirenet 868

(d) LoRANK 8



(e) Link labs LL-BST-8

(f) Lorrier LR2

Figure 3.10: Cost-saving analysis as a function of C_{CAPEX}^{Grid}

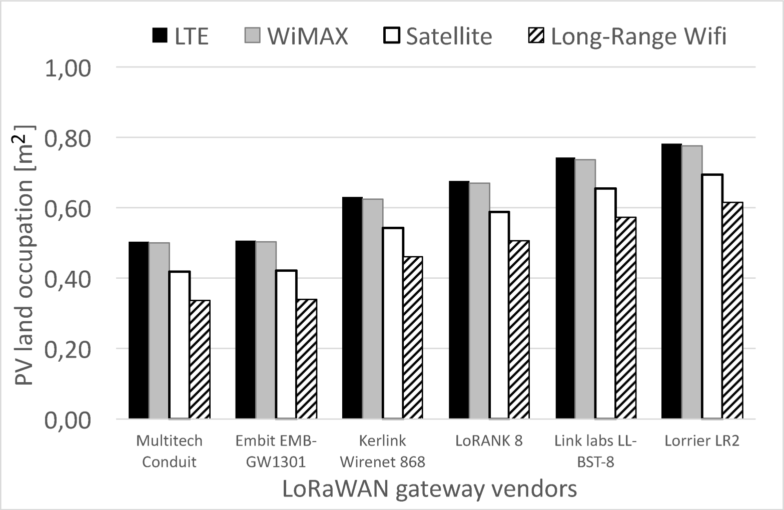


Figure 3.11: Land acquisition needed for different LoRa gateway vendors with multiple backhaul options

According to [179], the land acquisition for PV plant, i.e., PV_{LA} can be calculated as:

$$PV_{LA} = \frac{P_{PV\_rating}}{\eta_{panel}\ SR_{standard}}, \tag{3.9}$$

where η_{panel} and $SR_{standard}$ are the average efficiency of the solar module and the standard solar radiations, respectively. Solar modules composed of different materials, exhibit different system efficiencies. Here, polycrystalline silicon material has been considered, which undergoes $\eta_{panel} = 14\%$ and the standard solar radiations value is set as $SR_{standard} = 1kW/m^2$, that is the typical value for the southern part of Italy [192]. The computed land acquisition values are reported in Figure 3.11. As expected, the higher the P_{PV_rating}, the higher the computed land acquisition. However, the results in Figure 3.11 also demonstrate that the land acquisition is always lower than $1m^2$, which ensures a good space saving. Accordingly, the cost-saving analysis discussed herein simply assumes that $C_{land}^{PV} = 0$.

In conclusion, Figure 3.10 reports the cost-saving calculated, for all the combination of front-end and backhaul wireless links, as a function of C_{CAPEX}^{Grid}. It is evident that the higher the installation costs of LoRaWAN gateway due to grid connectivity, the higher the economic benefits gained by the proposed cable-less architecture. Nevertheless, in order to better evaluate the actual return on investment for this kind of infrastructure, it should be noted that network operators would be able to achieve their break-even when C_{CAPEX}^{Grid} is equal to the value reported in Table 3.6. In particular, Table 3.6 indicates the specific values of C_{CAPEX}^{Grid} for which the curves reported in Figure 3.10 intersect at the x-axis. The results should be interpreted as follows: in case the costs required for attaching a LoRaWAN gateway to the grid are higher than those reported in Table 3.6, network operators are able to achieve an instant profit throughout the lifetime of the deployed system. In addition, when the observation period is set to 10 years, the resulting economical gain is shown in Figure 3.10.

Anyway, in line with all the considerations previously reported, it is possible to finally remark that the cable-less LoRaWAN gateway leveraging the combination of Multitech Conduit chip is chosen as a front-end communication interface and the Long-Range WiFi adopted for the backhaul link is the most economically-efficient solution.

As reported in Figure 3.10, the Multitech Conduit gateway can achieve the break-even ranging from as low as €0.69K to €1.24K, when employed with Long-Range WiFi and LTE as a backhaul, respectively. Similarly, all the gateways achieve their break-even points in parallel when employing WiMAX and Satellite as a backhaul technologies ranging from €1.08K (Multitech Conduit) to €1.63K (Lorrier LR2). Due to the highest CAPEX incurred, Lorrier LR2 is able to achieve break-even as higher as €1.64K when employed with LTE as backhaul. An interesting aspect to note that the network operators start achieving their break-even when $C_{Grid-CAPEX}$ is as lower as €600 (in case of Multitech Conduit) because of lower $C_{PV-CAPEX}$. This trend undergoes an incline when $C_{Grid-CAPEX}$ gradually goes on increasing up to €1600 for break-even points when $C_{PV-CAPEX}$ is higher (in case of Lorrier LR2).

3.6.4 Carbon footprint analysis

Green networks are aimed at reducing a proportion of CO_2 that is continuously polluting our environment due to ICT infrastructures. Each kWh of electricity generated and provided by the direct grid roughly produces 386g of carbon, CO_2^{Grid}, as per the latest statistics by *International Energy Agency* [196]. The generation of a PV system also involves carbon emissions. But, supposing to distribute these CO_2 emissions among the lifetime of the system, it is possible to consider an equivalent amount of carbon

Table 3.6: Break-even points of different LoRa gateways against backhaul technologies

	Break-even points vs backhaul technologies **(K€)**			
LoRaWAN Gateway Vendors	LTE	WiMAX	Satellite	Long-Range WiFi
Multitech Conduit	1.09	1.08	1.08	0.69
Embit EMB-GW1301	1.10	1.09	1.09	0.70
Kerlink Wirenet 868	1.34	1.34	1.33	0.94
LoRANK 8	1.44	1.42	1.42	1.04
Link labs LL-BST-8	1.16	1.15	1.15	1.16
Lorrier LR2	1.64	1.63	1.63	1.24

emissions associated with a cable-less LoRaWAN gateway, CO_2^{PV}, equal to $20g/kWh$ as compared to $386g/kWh$ in case of direct grid connectivity[197]. By multiplying both the above quantities with the annual energy consumption of a single gateway, ($E_{year} = 24 \cdot 7 \cdot P_{tot}$, where P_{tot} is the peak power consumption as reported in Figure 3.4), gives an estimation of the difference in annual carbon emission of both the cases using equation 4.17.

$$CO_2^{savings} = (CO_2^{Grid} \cdot E_{year}) - (CO_2^{PV} \cdot E_{year}) = E_{year} \left(CO_2^{Grid} - CO_2^{PV} \right) \quad (3.10)$$

Having this in mind, the actual CO_2 saving is calculated by subtracting the amount of equivalent carbon emission per annum related to the PV plant from the one characterizing the conventional grid-powered approach, as depicted in Figure 3.12. The proposed cable-less solution is able to ensure a yearly CO_2 saving ranging from $24kg$ to $56kg$ for a single gateway. These encouraging statistics may lead towards tons of savings of carbon emission annually, when the proposed approach is applied on large-scale deployments. As a consequence, the cable-less option may prove to be of great value for network operators towards the deployment of next-generation green IoT infrastructures.

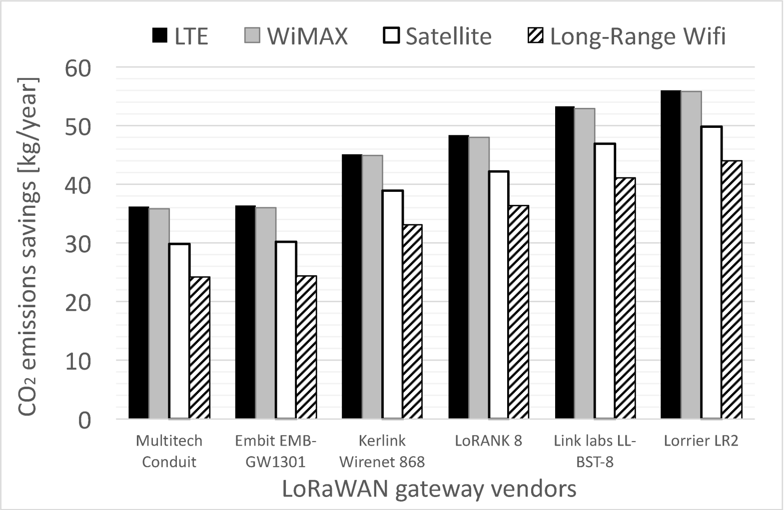


Figure 3.12: Carbon emission savings with cable-less gateway against multiple backhaul options

3.7 Summary and open research directions

This work proposed a cable-less Long Range Wide Area Network architecture, where the gateway is powered by an energy harvesting source and is connected to the rest of the network through a wireless backhaul link. Specifically, the conducted study clearly demonstrated that it is possible to feed a dual-radio gateway with a Photovoltaic plant with limited installation costs, while guaranteeing the quality of service requirements of heterogeneous Machine-to-Machine applications. The resulting architecture not only induces ease and scalability when compared to conventional design constraints, but it also provides a cost-effective and environment-friendly way enabling rapid Long Range Wide Area Network deployments, towards green communication models.

The proposed energy harvesting gateway model, however, introduces some new research issues to be tackled alongside the conventional challenges of radio access networks (like resource allocation, interference, and mobility management). In general, almost every kind of Renewable Energy Sources are prone to unpredictable behavior that causes a variable amount of energy scavenging depending upon various factors. For example, solar panels are expected to harvest only in the daylight in the ideal weather conditions. Similarly, a wind turbine produces intermittent amount of energy difficult to be predicted over a specific period. Hence, only introducing the notion of Renewable Energy Sources is never enough without proper considerations of network management techniques. It is not only significant to minimize the energy consumption but also towards achieving energy sustainability. It refers to defining a new set of algorithms, protocols, and procedures targeting Quality of Service (QoS) requirements keeping in view the amount of harvested energy in hand. The network should be smart enough to dynamically respond towards the fluctuating energy conditions on the storage. Although, dealing with these issues is out of the scope of this work but they deserve an active attention by the research community working on energy harvested wireless systems in the near future.

4

Energy harvesting LoRaWAN in the Industry 4.0; Cost efficiency optimization for industrial automation

Exploiting the advantages brought by long-range radio communications and extremely low power consumptions, LoRaWAN is capable to support low rate industry 4.0 services. Despite being energy-efficient, LoRa motes can still undergo frequent battery replenishments caused by the monitoring requirements of industrial applications. Duty-cycle constrained operations can partially face this issue at the expense of increased communication delays which, in turn, inflate higher costs due to damaged products on the production line. This chapter proposes a model to analyze this cost trade-off against different sensing intervals. It then evaluates LoRaWAN in industrial environment and strives to seek its suitability in a wide range of industrial use-cases. Moreover, it further highlights the impact of energy harvesting sources on this cost relationship mapping a way towards improved production efficiency.

4.1 Industrial Internet of Things; the fourth industrial revolution

The relentless expansion of today's Internet technology is driving automation processes towards the fourth industrial revolution. Industry 4.0 [198] argues about the innovative way of interaction between computing capabilities and process automation evolving the concept of 'Smart Industry'. The essence of Industry 4.0 [198] is the decentralized decision-making approach, based on real-time data collected through cyber-physical systems that constantly monitor the physical resources on the manufacturing line. These smart factories are able to suddenly react to unwanted events and avoid possible financial losses thanks to Predictive Maintenance (PM), Anomaly Detection, and Condition Monitoring systems. [199].

Industrial Internet of Things (IIoT) [200] is a recent wave of intelligent connectivity and communication that is being predicted as the game changer in redesigning and reshaping the concept of smart industry making possible the new industrial revolution. IIoT introduces a set of standards to enable the connectivity of a wide range of manufacturing equipment to a ekweb-based network and integrate this data for timely decision making. IIOT connects a wide range of sensor devices deployed across the production line to different analytic systems and aims at achieving the four major objectives. First, collection of sensor data in a cost effective and energy efficient way considering the fact that sensors are battery-powered in most of the cases. Second, interpretation of this data to transform it into an actionable information using some big data analytic tools. Third, presentation of this actionable information to an expert personnel or system at the right time for onward decision making. Fourth, achieving the desired performance improvement by taking preventive or corrective actions based on the data available. IIoT plays its part throughout the manufacturing process inducing the ultimate performance improvement that may lead towards billions of dollars of savings.

Pervasive connectivity technologies are the key enablers of the Industry 4.0 paradigm. In this context, LP-WAN [15] are quickly gaining momentum because of their inherent capabilities to match coverage, scalability, and energy efficiency requirements of IIoT deployments. Many different LP-WAN technologies are available nowadays including, but not limited to, LoRaWAN, Sigfox, NB-IoT, LTE-M1, Weightless, DASH7, and Ingenu [15]. Among them, LoRaWAN, Sigfox and, Weightless have already been proposed suitable for most of the Machine to Machine (M2M) communication scenarios in IIoT use-cases [201] because of their common characteristics (such as, low power consumption, high scalability with extended radio coverage, simple and low-cost network infrastructure).

Industry as well as academia, are equally convinced to explore a range of suitable LP-WAN technologies keeping in view the challenges laid down by Industrial IoT (IIoT) applications. Despite several low power technologies recently been floated on the surface to cater IIoT use cases, energy is still one of the major challenges for this kind of applications. It becomes particularly critical in the cases where the associated costs of the manufactured products are significantly higher and timely detection of different types of anomalies at various stages of the production line, can work towards avoiding huge financial losses for a smart industry. Achieving this milestone, simultaneously, involves a narrow line tradeoff between energy optimization and continuous monitoring during the production process.

Continuous sensing and data collection can obviously be beneficial for generating most updated alerts at one end, but it would cause frequent battery replenishment on the other side. Similarly, a fair sensing interval to generate alerts can well avoid the fast battery drainage hence prolonging the lifetime of sensor nodes but, sometimes, even a slight latency in popping-up an urgent alert costs a bulk of damaged products wasting the useful resources at the production line. Facing the critical interplay between latency, battery lifetime, and the requirements of Industry 4.0 applications requires a novel design methodology that accounts for all the costs and benefits entailed by LP-WAN deployments in smart industrial environments.

To bridge this gap, the following contributions are provided hereby: first, a model is presented to evaluate the lifetime of LoRa monitoring nodes. Second, battery replacement and damage penalty costs are evaluated to study their mutual relationship. Third, the evaluation of renewable energy sources to feed LoRa nodes in industrial environments is considered and a cost-benefits analysis is proposed.

Without lack of generality, this contribution will focus on the LoRaWAN architecture, but the methodology developed hereby can be applied, with some customizations, to any LP-WAN technology. Thanks to the proposed methodology, optimal sensing intervals (and related costs) have been derived in both harvesting and non-energy harvesting scenarios. It is encouraging to note that the aggregated cost in the presence of harvested energy can be reduced to one-fifth of the overall cost in the non-energy harvesting environment.

4.2 State of the art and essential comparison of different LP-WAN options

This section not only outlines the recent developments and proposals for monitoring the industrial processes but also discusses the potential of LP-WAN technologies targeting various industrial use-cases. The research community has already acknowledged to explore more wireless technologies for low bit-rate applications [15],[200][201] in addition to the ones conventionally been adopted (such as, ZigBee, Bluetooth, and RFID etc.) for industrial monitoring and control scenarios. Following are the few key examples of the recent developments in this area.

The first effort to highlight the significance of LP-WAN paradigm for long-term industrial scenarios in comparison to cellular architectures was made by [201]. The authors have identified the few suitable LP-WAN candidates to fulfill the strict requirements (such as, reliability and energy efficiency) imposed by IIoT networks. The assessment of existing LP-WAN solutions is performed overviewing the general strengths and weaknesses of this paradigm. They further support their arguments presenting a thorough analysis on the pros and cons of each of the LP-WAN solutions with special emphasis on LoRaWAN, Sigfox, and Weightless. The work classifies the existing industrial solutions into two different eras; short-range and long-range communication technologies for IIoT. The authors see the long-range LP-WAN solutions as the future of IIoT applications because of their features (such as scalability, long radio coverage, roaming and, energy efficiency).

Similarly, [58] is another to review the state of the art of LP-WAN technologies currently serving IoT applications. The authors start with highlighting the characteristics of IoT and how LP-WAN solutions meet the requirements imposed by a range of IoT applications. They thoroughly study two famous and widely accepted LP-WAN solutions; ultra-narrow band technology by Sigfox and Semtech's Chirp Spread Spectrum (SCC) technology introduced in LoRaWAN. According to the authors, these types of networks are supposed to capture approximately 55% of the total market share and all the giant players in the industry have taken a step ahead towards their widespread adoption. These two solutions have thoroughly been surveyed [58] in terms of their Physical (PHY) and MAC capabilities. They further held several experiments for both the solutions to evaluate their performance in terms of radio coverage and energy consumption. They argue that both the solutions are well capable to demonstrate the coverage in tens of kilometers with energy efficient battery powered devices lasting up to several years. Concluding their remarks, the authors revealed that private networks in LoRaWAN are the future of Industry 4.0 because of their suitability towards a range of IIoT use-cases.

Thanks to the inherent capabilities of IoT paradigm to provide pervasive connectivity among the devices and objects, it has led towards the fourth industrial revolution. According to [202], the existence of LP-WAN solutions has made it possible to achieve the goals anticipated by Industry 4.0. LoRaWAN and Narrow-Band Internet of Things (NB-IoT) are identified as the key players of this era to serve the use-cases of industrial monitoring and control applications. The authors review both the technologies presenting their pros and cons to exhibit the clear picture how they are suitable for different kind of use-cases. The authors argue that both the solutions target different set of applications as they both differ in terms of their characteristics to support IoT scenarios. They further continued to present their performance evaluation arguing LoRaWAN is the best in terms of cost, battery life and energy efficiency while NB-IoT is unbeatable with respect to Quality of Service (QoS), latency and, reliability. The authors concluded with their remarks that LoRaWAN is best suited for a bulk of industrial IoT use-cases including but not limited to air flow, temperature monitoring and, liquid presence detection.

Another insight of the LP-WAN solutions was presented by [203] which primarily throws light on the notion of Low Throughput Networks (LTN). LTN were thoroughly investigated by European Telecommunication Standard Institute (ETSI) towards their attempt to realize the future of low-bit rate IoT applications. The authors are aimed to evaluate the performance of different independent LP-WAN technologies flourished out before the standardization of LTN. For this purpose, the authors study three major technologies; LoRaWAN, Sigfox and, OnRamp. They investigate the innovative approaches employed by these technologies towards the solution of common IoT problems. Furthermore, they discussed the suitability of LTN for several application scenarios and how these LP-WAN technologies would perform better in those circumstances. The authors conclude that the studied technologies may only be suitable in the use-cases where the constraints like jitter, delay and, throughput are relaxed despite their higher radio coverage.

[204] highlights the importance of industrial monitoring and control processes in terms of productivity enhancements. The authors review most of the conventional wireless technologies used in the past and argue that this kind of techniques are not enough to meet the performance standards imposed by the new industrial revolution. They back their point by identifying a list of factors influencing performance goals (such as communication throughput, radio coverage, data security). The authors further added that extreme noise and whether conditions are also a major hindrance towards performance optimization. The authors are convinced that a cellular based IoT solution is inevitable to achieve required performance level. Hence, a design and implementation of IoT network is proposed for industrial monitoring and control based on GPRS wireless communication techniques. The authors conclude that their proposed IoT solution performs well in terms of identified parameters and IoT is the future of this kind of industrial use-cases.

Research community has also started studying different variations of LP-WAN solutions with different network topologies opposed to their inherent topological structure as in [205]. The authors consider Sigfox as the candidate because of its higher radio coverage almost equivalent to that of cellular networks offering a fraction of energy consumption compared to cellular networks. The authors investigate Sigfox based heterogeneous network architecture where they propose the combination of ultra-low energy consumption start network topology suitable for short range communication with a Sigfox gateway considered appropriate for long-range communications. This kind of infrastructure enables different IoT clusters of monitoring devices deployed across manufacturing line to communicate with Sigfox gateway at long distances that relays the communication onward to the Internet. The authors perform several experiments with energy modeling and claim that this kind of infrastructure guarantees a large coverage areas and longer battery life of end-devices deployed across the industry up to 4 years when employing 1000 mAh of battery.

The QoS was one of the parameters missing in the study of LoRaWAN for industrial monitoring as mentioned in [202]. [206] proposes analytical models to investigate LoRaWAN uplink (of class A device) with respect to several parameters like latency, throughput and collision rate while respecting the regulatory duty cycle restrictions in case of exponential inter-arrival times. The authors clear that their models also consider the cases of sub-band selection and combining as it has huge impact on the QoS. Although their model considers the European duty cycles but the authors claim that it is applicable to all coherent bands employed by other regions. The authors have conducted simulations to demonstrate the efficiency of their model and claim that their model is quite useful for the resource optimization in a cell for a preset QoS requirement and traffic model. The authors conclude with the remarks that their model for uplink traffic can also be combined with downlink of other monitoring devices belonging to different LoRaWAN classes (such as, B and C).

Despite being extremely energy efficient, most of the end-devices belonging to LP-WAN are still battery-powered. Frequent battery replenishments can be required to maintain ongoing operations, which obviously raises operational costs. Several works (e.g., [207]-[210]) have previously been presented to prolong the battery life of sensor nodes employing different techniques but, their strategies neither take into account the peculiarities of industrial environments, nor they discuss the cost of achieved lifetime in terms of damage penalty and, consequently, the battery replacement cost. For example, a classic approach to further extend battery life is to reduce the duty-cycle [209],[210] of sensing devices, which inflates communication delays. Unfortunately, in some industrial plants (e.g., automotive industry), the timely detection of anomalies at various stages of the production process is the only way to avoid huge financial losses(i.e., huge damage penalty).

Salient features of some of the major LP-WAN players, analyzed and marked suitable for industrial use-cases so far in the above literature, are reviewed below in Table 4.1. As each technology comes with its own set of pros and cons and distinct features as compared to others. Hence, the selection of single technology is not straight forward and involves several tradeoffs depending upon the possible use-case.

The choice of LoRaWAN has been made for further analysis in industrial monitoring and control applications because of the following reasons. First, LoRaWAN depicts the least current draw among all counterparts in similar conditions. Second, despite being

Table 4.1: Comparison of LP-WAN technologies studied for industrial monitoring applications

Parameters	**LoRaWAN**	**Sigfox**	**NB-IoT**
Spectrum	Unlicensed ISM	Unlicensed ISM	Licensed LTE Bandwidth
Business Model	Alliance	Proprietary	Proprietary
Duplex Mode	Half	Half	Half
Modulation	LoRa(based on CSS)	BPSK	QPSK
Bandwidth	125 kHz	100 Hz	180 kHz
Data Rates	290 bps-50 kbps	100 bps	250 kbps
Current Draw	28mAh @13 dBm	49 mAh	120-300 mAh
Sleep Mode	1 μAh	1.3 μAh	5 μAh
Coverage	157 dB	149 dB	164 dB
Uplink Latency	<2 s	<3 s	<10 s
Payload Size	51-243 Bytes	12 Bytes	1500-1600 Bytes
Security	32 Bit	16 Bit	3GPP(128-256 Bit)
Scalability	Medium	Low	High
Interference Immunity	High	Low	Low
Spectrum Cost	Free	Free	>$500 million/MHz
Deployment Cost	$100-1000/gateway	$700-1200/gateway	$15000/base station
Range	2-5km urban, <15km suburban	10km urban, 50km rural	<15km urban, <35km rural

the proprietary physical layer solution itself, LoRa has an open source protocol stack as LoRaWAN that seems more open to adopt. Third, it enjoys a reasonable trade-off for throughput while operating in unlicensed ISM band. Fourth, LoRaWAN packets experience minimum uplink latency that can be of significance in industrial monitoring scenarios in addition to the latency due to sensing interval that may cause huge damage penalty. Fifth, cost is another decisive parameter that may cause standing LoRaWAN far apart from its counterparts with an added advantage of fair scalability potential within an industry. Last, but not the least, LoRaWAN has got significant attention in recent years because of its rapid adaption for public network infrastructures already deployed by several network operators.

4.3 LoRaWAN for Industrial Monitoring

This section starts with an overview of LoRaWAN and throws light on the feasibility of this technology for industrial monitoring applications. Then, it covers several important parameters that provide basis and justify the reasons to fit it in a number of IIoT use-cases. Furthermore, it follows an in depth analysis on the capabilities of LoRaWAN to demonstrate its suitability for a variety of applications in industry 4.0 and how it can effectively serve a bulk of industrial monitoring use-cases.

LoRa has emerged as a robust physical layer proprietary solution in last few years introduced by French company Cycleo, later acquired by Semtech. As the name suggests, LoRa is, based on Chirp Spread Spectrum (CSS) modulation technique, intended to provide long radio coverage. CSS itself is not the new technique and has widely been employed in numerous military applications to achieve communication between far apart areas and resilience against interference. LoRa can be seen as the first ever very low-cost commercial implementation of CSS technique which provides a fair tradeoff between data rate and sensitivity. LoRa operates on sub-GHz ISM band and employs wide channel bandwidths that enables LoRa to provide Adaptive Data Rates (ADR) with variable gains. Following these peculiarities, LoRa has been adopted as a physical layer technology by LoRaWAN protocol stack that is being promoted by an Alliance (known as $LoRa^{TM}$ Alliance) of over 160 members worldwide including, but not limited to, BM, Cisco, Orange, ZTE and, Actility and many others [211].

Because of its matchless characteristics to meet most of the requirements imposed by industrial monitoring use-cases, LoRaWAN has recently been recommended the right choice for this kind of requirements [15],[200][201]. To date,tehre are no studies available to analyses LoRaWAN's strengths and weaknesses for industrial monitoring applications. This section investigates the capabilities of LoRaWAN when deployed in a smart industry. To this end, energy consumption of LoRa monitoring devices is evaluated assuming Unidirectional (uplink) communication initiated by periodic transmitters. Here, the frequency of periodic transmitter (monitoring device) to sense and report an anomaly plays a significant role. Various sensing intervals are considered to investigate the average battery life of LoRa monitoring devices against their operation on different LoRaWAN transmitting power and spreading factors (ranging from 7 to 12). Furthermore, the capacity of LoRaWAN is analyzed using different spreading factors.

The data transmitted by LoRa monitoring devices to the gateway is crucial to the management as it may directly influence the industrial revenue by inducing unwanted costs. Thanks to the inherent capabilities of IIoT to provide continuous monitoring and control of production line for the industry 4.0, this type of costs can significantly (if not entirely) be reduced to increase the revenue. The expert systems are employed in smart industries to take preventive or corrective actions in case an anomaly is detected. These systems are aimed at reducing the damage penalty as minimal as possible by taking actions on early stages. For this reason, expert systems directly control LoRa monitoring devices spread across the industry through an application interface.

The Airtime of LoRa monitoring devices is evaluated below in Table 4.2 employing Eq. 1.1 to 1.7 presented in Chapter 1. Here, it is important to note that all the other LoRa configurations settings are assumed constant during this evaluation which includes payload size = 15 bytes, LoRaWAN header size = 13 bytes, Explicit header = on, CRC = enabled, Low DR optimizer = auto, CR = 4/5, Preamble symbols = 8 and, Bandwidth = 125kHz and, Frequency = 865MHz. Each of the parameters in LoRaWAN configuration is important and modifying any of the settings would consequently influence the air time. The same set of values is assumed throughout the evaluation that would be discussed with detail in subsequent sections

Table 4.2: Air Time evaluation of LoRaWAN for different LoRa configuration settings

Spreading Factor	T_{sym} − (ms)	$T_{preamble}$− (ms)	*No. of Payload Symbols*	$T_{payload}$	*Air Time - =*$T_a(ms)$	Time b/w packet starts (s)		
						d=0.1%	*d =1%*	*d =10%*
SF7	1.024	12.544	33	33.792	46.336	46.34	4.63	0.46
SF8	2.048	25.088	33	67.584	92.672	92.67	9.27	0.93
SF9	4.096	50.176	28	114.688	164.864	164.86	16.49	1.65
SF10	8.192	100.352	28	229.376	329.728	329.73	32.97	3.30
SF11	16.384	200.704	28	458.752	659.456	659.46	65.95	6.59
SF12	32.768	401.408	23	753.664	1155.072	1155.07	115.51	11.55

4.4 System Model

The system model envisaged in this chapter considers an implementation of LoRa based monitoring devices in the industrial environment as shown in Figure 4.1. Being a part of IIoT, the LoRa end-devices monitor several industrial parameters (such as pollution monitoring, fire detection, flow level monitoring, leakage detection, and temperature monitoring).

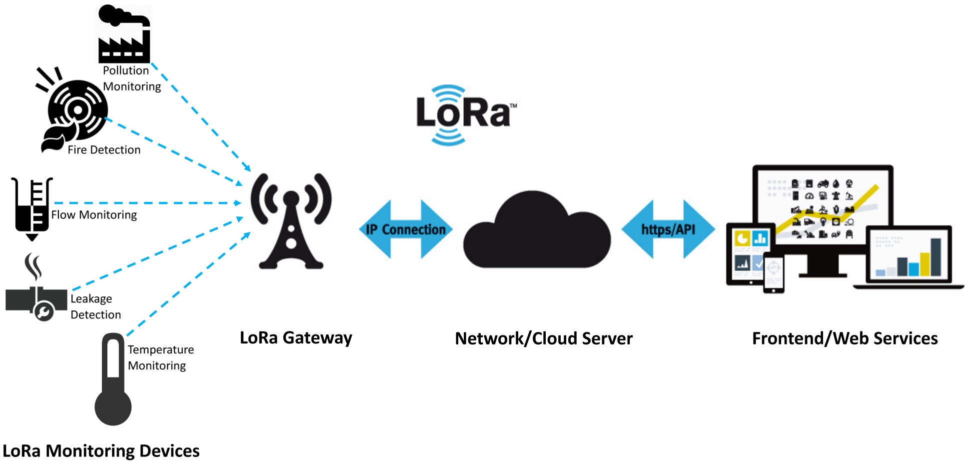


Figure 4.1: LoRaWAN architecture implemented in an industrial environment

Table 4.3: LoRaWAN assumed parameters for the lifetime evaluation

LoRaWAN Parameters	**Values**
Application Payload	1-3Bytes
Modulation Technique	LoRa (based on CSS)
Spreading Factor (SF)	7-12
Coding Rate	4/5
Bandwidth	125kHz
Preamble Symbols	8
Transmit Power	$14dBm$
Distance between motes and the gateway	1200m

The LoRaWAN configuration settings considered in the lifetime evaluation are presented in Table 4.3. It is pertinent to note that an average energy consumption reading for different LoRa SFs is considered in lifetime evaluation. Furthermore, no variation in the energy consumption is observed until the application payload size of $3Bytes$ which seems appropriate to several industrial applications for reporting an alert to the expert systems. Being battery-powered, LoRa end-devices conventionally follow periodic transmission intervals to prolong their operations. The monitoring devices are put on sleep after each transmission interval until their next measurement. Let the pause time between two consecutive monitoring slots of a LoRaWAN device is sensing interval, ΔT_{sense}, and Δt_s be the duration when the end-device remains in sleep mode then, the sensing interval can be expressed as:

$$\Delta T_{sense} = \Delta t_s + \Delta t_{setup}. \tag{4.1}$$

where, Δt_{setup} is the time required for a monitoring node to switch between active and sleep modes (i.e., $2.\Delta t_{switch}$). Sensing interval is critical to expert systems towards timely decision making. At one end, short sensing interval helps detecting the anomaly at early stages and enhances the productivity of a smart industry yielding more revenues. On the other hand, increased transmission duty-cycle of monitoring devices causes short battery life hence frequent battery replenishments are needed. Similarly, where long sensing interval makes it possible for monitoring devices to maintain their operation for several years, it may simultaneously incur delays in fault detection scenarios hence, production efficiency is on the stake.

4.4.1 Battery Life

Several sensing intervals have been considered ranging from one to five minutes to investigate the impact of varying I_s on the energy consumption of LoRa monitoring devices. To this end, LoRa monitoring devices from Semtech Inc. are studied considering the current draw of their chipset as 44 mA when transmitting with 14 dBm output power [212]. The monitoring devices are assumed to be the periodic transmitters only in a unidirectional way. They conventionally follow active and sleep modes where average current draws in sleep and switch mode ($\mu(I)_s$ and $\mu(I)_{sw}$) are 100 nA and 21.9 mA, respectively [212].

Then, the mean charge, $\mu(Q)$, in each state (active, sleep, and switch) can be evaluated considering current draws of Semtech's LoRa monitoring node in different modes and time duration when a node stays in that state (e.g., $\mu(Q)_{TX} = \mu(I)_{TX} \cdot \Delta t_{TX}$; where, $\mu(I)_{TX}$ is the average current draw of monitoring node in transmit mode and Δt_{TX} is the duration of active period). The total charge, $\mu(Q)_{tot}$, is the summation of the products of average current flow and the time duration in all possible states and can be seen as:

$$\mu(Q)_{tot} = \sum_{S} \mu(I)_S \cdot \Delta t_S, S \in \{TX, s, sw\} \tag{4.2}$$

As the total mean energy, $\mu(E)_{tot}$, is the product of total average charge and voltage applied on *SX1272* end-device so it can be evaluated as:

$$\mu(E)_{tot} = \mu(Q)_{tot} \cdot V_{SX1272} \tag{4.3}$$

Likewise, the average energy consumed per day, $\mu(E)_{day}$, and the average energy consumption during a whole year can also be calculated using Eq. (3). Now, the battery life (in years) is evaluated assuming the total battery capacity, $(Cap)_{batt.}$, of 1000 mAh (*11880J @ 3.3V*):

$$\mu(Life)_{batt.} = \frac{(Cap)_{batt.}}{\mu(E)_{day}} \cdot 365 \tag{4.4}$$

4.4.2 Battery replacement cost

The battery replacement cost of LoRa monitoring nodes deployed throughout the production line is the first significant cost that is considered critically while designing the monitoring and control system. This cost can further be split into three types of costs; *battery purchasing cost*, *installation cost*, and *the dispose-of cost* for the old battery. The first one is taken as the fixed cost neglecting the inflation factor with time while the second one depends upon the type of industry and the replacement complexity of LoRa monitoring node whose battery needs replenishment. For example, the monitoring nodes installed internally inside a machinery would incur more labor cost due to the complexity of task as compared to the one installed on the relatively simpler spot. Like purchasing cost, the dispose-of cost can also be assumed as a fixed cost. A set of assumptions followed to evaluate the associated battery replacement cost is presented in Table 4.4.

Battery purchase cost, $C_{batt.}$, can be respected as the total cost of purchasing the required number of batteries in a time period and can be evaluated as:

$$C_{batt.} = C_b \cdot N_{cyc} \tag{4.5}$$

Table 4.4: Assumed values for cumulative battery replacement cost evaluation

Cost Parameters	**Assumed Values**
Average battery life calculated for LoRa monitoring device @14dBm transmitting power (years)	0.10 - 5.14
Cost assumed per battery (£), C_b	3.7
Time period considered (years), T	20
The number of batteries per node	1
Variable battery installation labor cost per node (£), C_r	3.5 - 10
Dispose-of cost per node in period T (£), $C_{diss.}$	0.10

where, C_b and N_{cyc} are the cost incurred to purchase a single battery and number of replacement cycles required in a given time period, respectively. Here, it is important to note that a time period of 20 years is considered for this cost evaluation because it is believed to be the fair lifetime achievable through LoRa monitoring nodes in energy harvesting scenarios. Similarly, cumulative installation cost, $C_{inst.}$, is the variable labor cost that can be calculated as:

$$C_{inst.} = C_r \cdot N_{cyc} \tag{4.6}$$

where, C_r is the variable replacement labor cost per node depending upon the complexity of spot. The battery dispose-of cost, $C_{diss.}$, is the cost incurred on disposing-of the replaced batteries that is not usually higher but it may still be significant in case of large-scale network deployment where thousands of nodes need replacement in a time period. $C_{diss.}$ is calculated assuming £1400 as the average dispose-of cost per ton of battery wastage from the recent statistics published by UK Government authorities [213]. Hence, the total battery replacement cost in pounds, C_{tot}, can be seen as the summation of these costs in a time period of twenty years for LoRa monitoring node in the system, and can be expressed as:

$$C_{tot} = \sum_{s} C_s, s \in \{batt., inst., diss.\} \tag{4.7}$$

4.4.3 Damage penalty

The damage penalty can be referred as the cost of damaged products on the production line due to a possible delay in anomaly detection. This delay can be seen as damage interval, $\Delta T_{dam.}$ and expressed as:

$$\Delta T_{dam.} = t_d - t_o \ ; \ 0 \leqslant \Delta T_{dam.} \leqslant \Delta T_{sense} \tag{4.8}$$

where, t_d and t_o are the anomaly detection time and anomaly occurrence time, respectively. Let $P_{dam.}$ be the damage penalty and $R_{prod.}$ be the rate of production at the production line (taken in terms of the number of products manufactured per minute), then the damage penalty can be calculated as:

$$P_{dam.} = \Delta T_{dam.} \times R_{prod.} \times C_{unit} \tag{4.9}$$

where, C_{unit} is the unit cost of production assumed for a specific unfinished product. As the domain of damage interval is increased with increasing value of ΔT_{sense}, the damage penalty also keeps on increasing. The damage penalty is evaluated for different categories of products like cheap, medium, expensive, and very expensive as shown in Figure 4.5 .

Table 4.5: Product categories considered along with associated unit costs and production rates

Product Catagory	**Unit Cost,** C_u (£)	**Rate of Production,** $R_p(products/min)$
Cheap	10	30
Medium	70	6
Expensive	150	3
Very Expensive	500	1

4.5 Energy harvesting for industrial monitoring

Energy harvested from renewable energy sources, available in the industrial environment, can play its role to improve both performance and production efficiency in the industry. It is difficult to predict the exact amount of energy harvested from various renewable sources in advance for fairly long intervals. However, it is possible to determine this amount for shorter intervals depending upon the type of harvester and environment. It is also one of the challenges while balancing the tradeoff between energy consumption and sensing interval optimization for the monitoring nodes during the production process. Energy scavenging paradigm further complicates the evaluation of the exact amount of energy available at hand to adopt a fair policy for sensing interval selection to maintain the desired performance level.

For making the evaluation as simple as possible, an average harvesting potential per day for three different renewable energy sources is considered in this study (see Table 4.6). This potential for harvesting energy is commonly available in most of the industrial environments and has already been exploited by industrial monitoring applications reported in [214, 215]. The three harvesting sources along with exploitable average energy harvesting potential per day are listed in Table 4.6. First, artificial light bulbs are considered with a potential to harvest a fair amount of energy during the office hours. Second, the harvesting potential due to change in temperature is reported to scavenge reasonable amount of energy at two different temperature gradients. Third, the amount of energy harvested due to radio signals following the assumptions in Table 4.6.

Table 4.6: Considered energy harvesting sources with their average potential

Energy Harvesting Source	**Assumptions**	**Harvesting Potential (J)**
Photoelectric (artificial light sources)	Average of office hours (8 hours @200 lx)	4.3
Thermoelectric (internal and external heat difference)	10 hour@ 5^oC and 5 hours @10^oC	6.2
RF Energy (radio signals within the plant)	3W transmitted through 5m distant source @ 9MHz	1.8
The total amount of harvested energy	Considering three different sources	12.3

Surplus harvested energy from the industrial environment may be useful for achieving two significant milestones. First, it may serve to reduce the energy requirement of battery-powered monitoring devices by enabling them to operate on harvested energy when available. Monitoring devices only go for a battery-powered operation in the absence of harvesting energy that would eventually prolong the battery life. Secondly, as the sensing interval reciprocates damage penalty in an industrial environment, the newly harvested energy could be employed to seek the tradeoff by shrinking the sensing interval up to a fair percentage without compromising on the battery life. This flexibility can dramatically improve the production efficiency of various product lines in industry 4.0 depending upon C_u and R_p of the manufacturing plant.

4.5.1 Battery life with energy harvesting

Let $S = \{e_1, e_2, ..., e_n\}$ be the amount of harvested energy being added to the system through n different renewable energy sources where, $n \in \mathbb{N}$, then the energy available in the buffer can be represented as:

$$e^b = \sum_{s=1}^{n} e_s \tag{4.10}$$

Now, dividing the total harvesting time into K different slots $\{1,\ 2,\ 3, ...,\ k-1,\ k\}$ $\mid k \in \mathbb{R}$, the amount of harvested energy available within the energy buffer at the end of slot k can be expressed as $e^b_k = (e^b_{k-1} - e^i_k) + e^h_k$; where, e^b_{k-1} is the available energy in the buffer until the previous slot, e^i_k is the amount of instantaneous energy consumed during current slot k, and e^h_k is the newly harvested energy added to the system in current slot k.

Here, the amount of harvested energy over all k slots can be expressed as follows realizing the above expression:

$$\int_0^k E^b dk = \left[\int_0^{k-1} e^b dk - \int_{k-1}^{k} e^i dk \right] + \int_{k-1}^{k} e^h dk \tag{4.11}$$

given that $\int_0^{k-1} e^b dk > \int_{k-1}^{k} e^i dk$ for an uninterrupted operation. This is the amount of energy left in the energy buffer after slot k. Hence, substituting the value of e^b from Eq. (4.10) in Eq. (4.11):

$$\int_0^k E^b dk = \left[\sum_{s=1}^{n} \int_0^{k-1} e^b_s dk - \sum_{s=1}^{n} \int_{k-1}^{k} e^i_s dk \right] + \sum_{s=1}^{n} \int_{k-1}^{k} e^h_s dk \tag{4.12}$$

If there are k slots in a day, then the amount of energy harvested per day, E^h_{day}, is equal to the amount of energy added to the system over k time slots as follows:

$$\mu(E^h)_{day} = \int_0^k E^b dk \tag{4.13}$$

Now, realizing the above equation, we can rewrite the Eq. (4.12) as:

$$\mu(E^h)_{day} = \left[\sum_{s=1}^{n}\int_{0}^{k-1} e_s^b dk - \sum_{s=1}^{n}\int_{k-1}^{k} e_s^i dk\right] + \sum_{s=1}^{n}\int_{k-1}^{k} e_s^h dk \tag{4.14}$$

Hence, the new energy requirement per day, $\mu(E')_{day}$, can easily be evaluated as a difference of previous energy demand drawn per day from Eq.(4.3), $\mu(E)_{day}$, and the newly harvested energy per day,$\mu(E)_{day}^h$, and can be represented as:

$$\mu(E')_{day} = \mu(E)_{day} - \mu(E)_{day}^h \tag{4.15}$$

Once the new energy requirement per day has been established, the new battery life of LoRa monitoring nodes can be evaluated employing Eq. (4.4) following the same set of assumptions regarding battery capacity and applied voltage (*1000 mAh @ 3.3 V*) as in non-energy harvesting life calculations. This new life would also lead to significant reduction in total battery replacement cost, C_{tot}, without affecting the damage penalty.

4.5.2 Sensing interval with energy harvesting

Similarly, sensing interval can also be contracted in the presence of energy harvesting sources without compromising on the existing battery life. The extent of this contraction can rightly be assumed equal to the relaxation in energy quota due to harvested energy. It is the ratio of the average harvested energy per day to the previous energy demand per day. Hence, the new sensing interval in presence of energy harvesting sources, $\Delta T'_{sense}$, can be expressed as:

$$\Delta T'_{sense} = \Delta T_{sense} - (\Delta T_{sense} \cdot \frac{\mu(E)_{day}^h}{\mu(E')_{day}}) \tag{4.16}$$

The new sensing interval would serve to significantly reduce the damage penalty, $P_{dam.}$, while fixing the battery replacement cost.

4.6 Results and Discussions

This section spans the results of LoRaWAN evaluation following the proposed model (elaborated in Section 4.4) along with a detailed discussion on these results and can be divided into two sections; standard LoRaWAN evaluation for industrial monitoring and LoRaWAN in industrial monitoring with energy harvesting capabilities. The first sub-section encompasses the results on several critical performance indicators (such as, energy consumption, battery life, spreading factor support, battery replacement cost, damage penalty, and total cost) while evaluating LoRaWAN deployed in industry 4.0. The second sub-section highlights the same indicators of LoRaWAN but after exploiting the energy harvesting capabilities present within industrial environment and it draws a comparison between the results taken in industrial environment in both energy harvesting and non-energy harvesting scenarios.

4.6.1 LoRaWAN evaluation in industrial monitoring scenarios

4.6.1.1 Energy consumption

Energy consumption can be seen as the foremost LoRaWAN parameter evaluated in the industrial environment. It serves as the primary step to evaluate the battery life of a LoRa monitoring node and it can be evaluated as a product of total charge consumed and the applied voltage by Eq. (4.3). Figure 4.2 presents the average energy consumption of LoRa monitoring node per day against a range of fair sensing Intervals. The average energy consumption is the average value of all the energy consumptions reported while operating on different LoRaWAN spreading factors as each of the spreading factors leads to different active and sleep times depending on its air time. Figure 4.2 reports the maximum value of energy consumption (almost 85 J a day) when the node senses every minute. It is obvious to note that the average consumption goes on decreasing as sensing interval is increased. For example, the average value of energy consumption per day is at the minimum when LoRa monitoring node senses and reports for an anomaly every five minutes. It can be seen as the best-case scenario with respect to longer battery life in standard LoRaWAN.

4.6.1.2 Battery life with different transmitting powers

After evaluating the energy consumption of LoRa monitoring devices, the average battery life can also be calculated as reported in Figure 4.3. Similar to the average energy consumption, average life is the average value taken when the monitoring device operates on different spreading factors. As LoRa monitoring devices are capable of transmitting with different output powers, the results in Figure 4.3 are taken with four

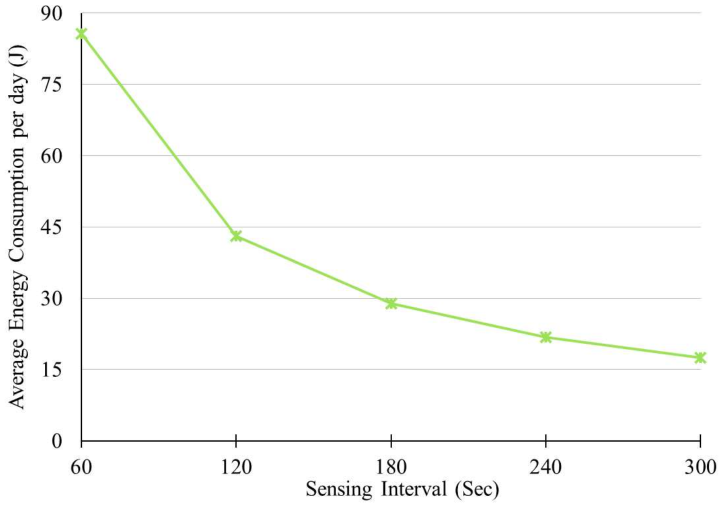


Figure 4.2: Average energy consumption per day against different sensing intervals

different power configurations ranging from 13 *dBm* to 20 *dBm*. It is significant to note that monitoring devices are unable to achieve a battery life of more than two years under any configuration until the sensing interval reaches 1 min as seen in Figure 4.3. The battery life is significantly increased between 1 *min* to 5 *min* sensing interval. The maximum battery life (of approximately 8 years) can be observed in case of 13 *dBm* as the current draw in this configuration is minimum (28 mA) as compared to configuration of 20 *dBm* when the monitoring node undergoes maximum current draw (125 mA) which yields less than 2 years of battery life.

Figure 4.3 presents the life time of monitoring nodes with different possible power configurations. However, 14d Bm is the maximum transmission power allowed for an emitter in 1% duty cycle sub-band under European legislations for transmission power restrictions. It can be considered sufficient in industrial monitoring applications where the LoRa gateways are in the same vicinity and signal does not need to travel across longer distances, unlike other LoRaWAN applications. Hence, the rest of the evaluation procedure would assume all the calculations with respect to 14 *dBm* power transmission throughout this study. Figure 4.4 zooms into the 14 *dBm* power configuration setting where the monitoring nodes successfully achieve a life time of 5 years when they wake back every 5 *min* to measure and transmit. The monitoring nodes with sensing interval of less than 1 *min* are not able to even exceed the life time of one year. Here, it is

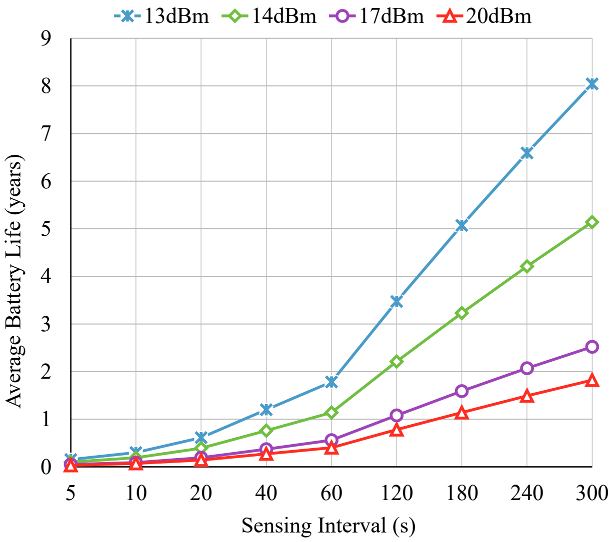


Figure 4.3: Battery Life of monitoring device considering different sensing intervals and transmitting powers in LoRaWAN

interesting to note that the delay of every minute after the first minute in the sensing interval yields almost one-year increment in the overall battery life of monitoring node in this case.

4.6.1.3 Sensing intervals compatible with LoRaWAN

Maximum number of messages in a day can be another significant indicator to observe in industrial monitoring scenarios when choosing the different sensing intervals. Figure 4.5 gives an overview of the maximum number of messages that can be transmitted by any monitoring node deployed across the production line when different active and sleep periods are selected. It can be observed from Figure 4.5 that every minute of shrinkage in the sensing interval doubles the number of messages that can be transmitted from 5 *min* to 1 *min* throughout the day without following any constraints. The maximum number of messages can be transmitted when the monitoring nodes wake up every 5s throughout the day which yields maximum capacity on the cost of very short battery life. As most of the energy is consumed during active periods when the monitoring nodes are continuously measuring and transmitting the data to increase the probability of anomaly detection.

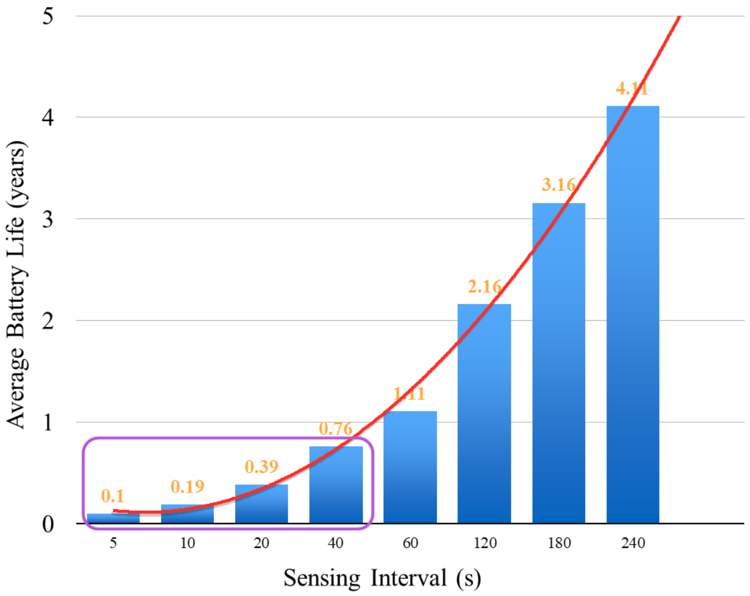


Figure 4.4: Average battery life achievable against different Sensing Intervals assuming 14 *dBm* transmission power considered for industrial monitoring use-cases

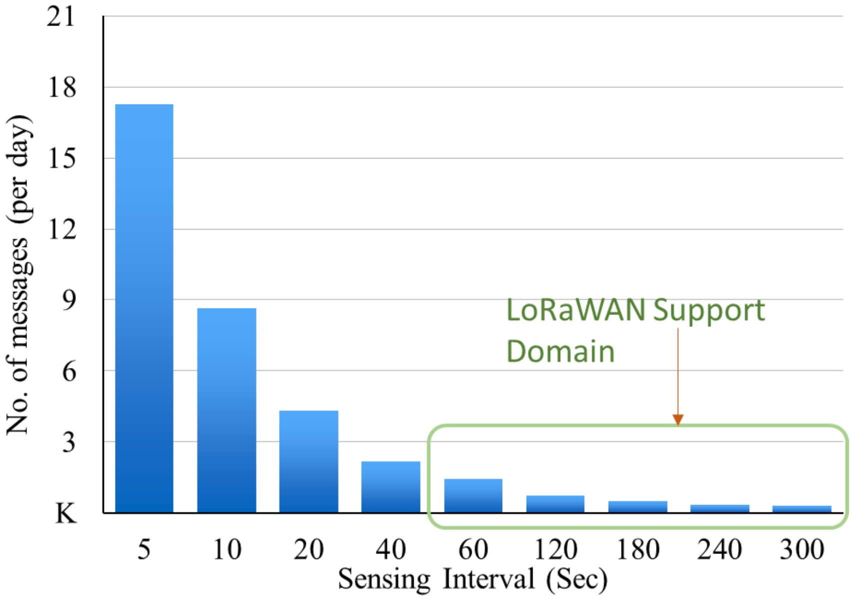


Figure 4.5: Maximum number of messages per day assuming different sensing intervals

The number of messages demonstrated in Figure 4.5 is ideal and in most of the cases, it is practically unachievable while deploying LoRaWAN in industrial monitoring scenarios because LoRaWAN comes with certain limitations and constraints as discussed earlier. LoRaWAN can only support limited number of messages per day as permitted by the local duty cycle constraints. For example, number of messages per day in LoRaWAN depends on the two different factors. First, the choice of spreading factor for communication as every *SF* in LoRaWAN incurs different air time. Second, duty-cycle of a particular sub-band available for communication as there may be multiple sub-bands at each transmission with different duty-cycle restrictions (e.g. 0.1%, 1%, or 10%). Figure 4.6 shows how different sensing intervals are supported by different *SFs* in LoRaWAN in terms of number of messages compatibility. For example, only SF7 can support the maximum number of messages with 5 s sensing interval and monitoring nodes cannot employ other spreading factors available in LoRaWAN to practically transmit this number of messages. Figure 4.6 concludes that LoRa monitoring nodes do not support the sensing intervals lesser than 40 s as not all the SF in LoRaWAN can be employed for communication in these cases. It implies that fair range for sensing interval consideration in LoRaWAN can be in terms of minutes (i.e., from 1 *min* to 5 *min*). Therefore, the rest of the results are taken to assume this range of sensing intervals.

4.6.1.4 Statistics for battery replacement cost

The battery replacement cost is the first type of cost that an industry may consider significant to increase the revenue. It includes the cost of purchasing the new battery, its replacement labor cost and the cost incurred to properly dispose-of the used batteries. The replacement labor cost can be variable depending upon the complexity of spot where the LoRa monitoring node is installed while the other two costs can be fixed ignoring the inflation rate with time.

The higher management in a smart industry may follow different battery replacement models depending upon their suitability but they always find it difficult replacing the batteries of monitoring nodes for two reasons; (1) it incurs a lot of industrial resources in terms of cost and time, (2) the entire production process needs to be in non-operational state that results huge financial losses and deteriorates production efficiency. Despite all the facts, there may still be some nodes whose replenishment is

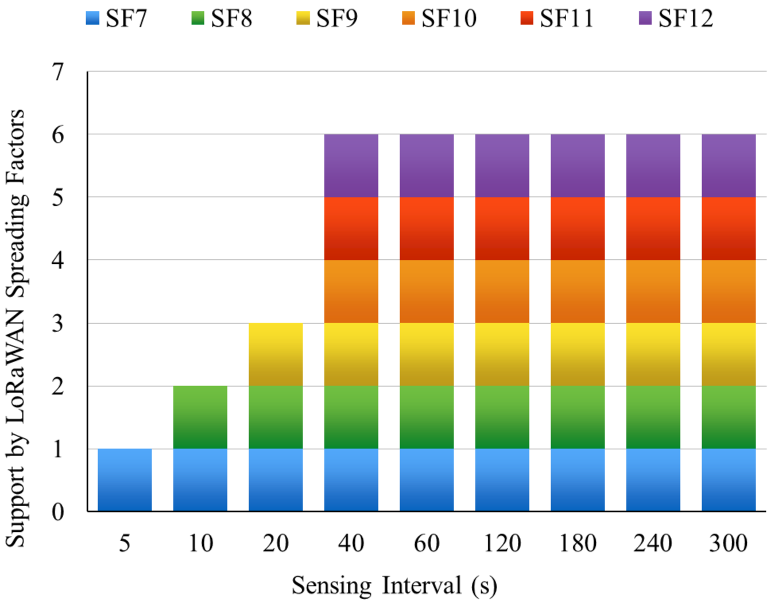


Figure 4.6: LoRaWAN support for various Sensing Intervals in case of 1% duty cycle restriction imposed by EU regulations

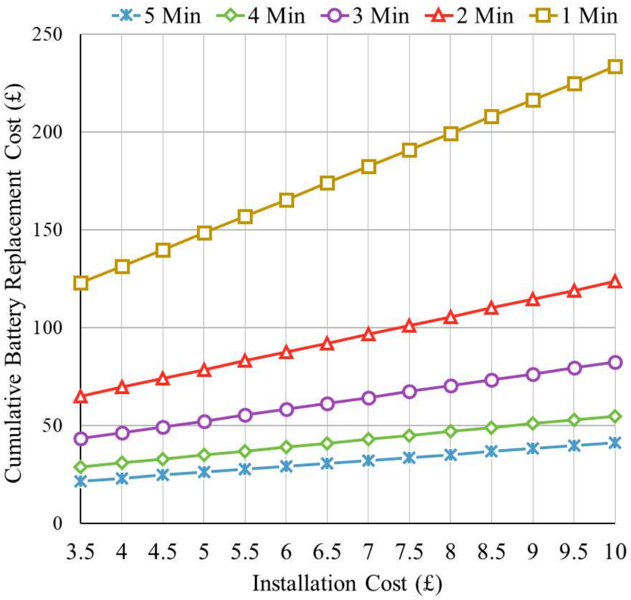


Figure 4.7: Cumulative Battery Replacement Cost against variation with respect to complexity

almost impossible for many reasons. Figure 4.7 presents cumulative battery replacement cost when the variation in the installation cost is considered between the range of £3.5 to £10 per replacement with respect to complexity of the spot where the monitoring node is installed within a smart industry. These costs are anticipated for a fair range of sensing intervals identified in Figure 4.6. It is obvious from Figure 4.7 that cumulative battery cost goes on increasing when we go on shrinking the sensing interval because more number of battery replacement cycles are needed in 20-year time period when the monitoring nodes wake up more frequently (e.g., in case of 1 *min* sensing interval). Similarly, replacement cost variation does not affect much when the sensing interval is as longer as 5 *min* and it does not go beyond £50. The gap between each pair of adjacent curves goes on widening despite an equal increase in the sensing interval, which argues an exponential increment in battery replacement cost with respect to sensing interval.

4.6.1.5 Statistics for Damage penalty

The damage penalty can be seen as the second type of cost but higher enough to be paid significant attention by the administration of a smart industry. It refers to the cost of damaged products on the production line when an anomaly is detected far later that a corrective action cannot even rescue the financial losses. Figure 4.8 presents an overview of the damaged penalty against the damage interval when the unit cost is £500 and rate of production is 1 *per min*. It can be observed from Figure 4.8 that the penalty goes on doubling when damage interval is increased every minute starting from 1 *min* to maximum of 5 *min*. It remains unchanged for the duration of each minute until entering into the next minute and keeps on increasing linearly with time. It implies that reducing the damage interval would end up dropping down the damage penalty but the damage interval would always span within the range of sensing interval. The longer the sensing interval, the longer the damage interval it may cause as smart systems can only detect anomalies to take corrective actions when they first hear the LoRa monitoring nodes after the anomaly occurrence. The best case can be the minimum value of sensing interval so that to avoid any delays in detecting the anomalous situation. Similarly, the worst case may be the longest sensing interval when the anomaly was occurred just after the previous cycle when last reported by the

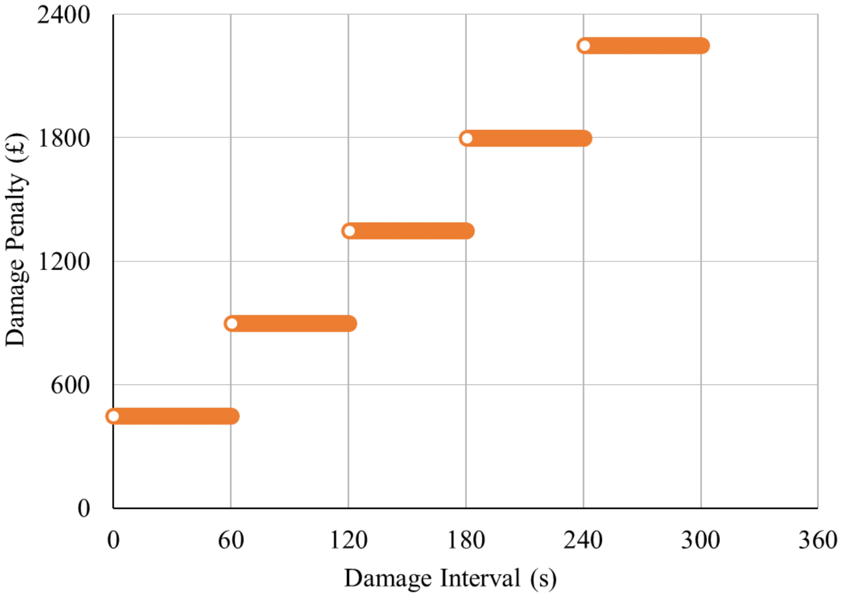


Figure 4.8: Damage Penalty overview with respect to various Damage Intervals when $C_u = £450, R_p = 1/min$

monitoring node and the smart system would be able to detect this anomaly in the next cycle at the earliest after waiting for the whole sensing interval (e.g., $\Delta T_{sense} = 5m$).

Figure 4.9 compares four different product lines from industry 4.0 with different unit costs and production rates given in Table 4.5. As discussed earlier, all four cases depict the same trend for damage penalty while moving along sensing intervals. Although, there is not a noticeable difference between the damage penalty of all four cases on lower part of sensing interval, but as we move on increasing the sensing interval, the difference appears to be significant. The product with minimum unit cost with higher production rate seems to be the most ideal case when the penalty does not go beyond £1500 even with the longest sensing interval (i.e., *5 min*). The damage penalty may go as higher as £2500 in case of maximum unit cost and lowest production rate following the same sensing interval.

4.6.1.6 The overall cost in non-Energy harvesting scenarios

The overall cost includes both types of contradictory costs evaluated previously; battery costs and damage penalty. Figure 4.10 throws light on an overall picture depicting both types of cost to estimate a clear contribution of each type of cost in the overall cost. To

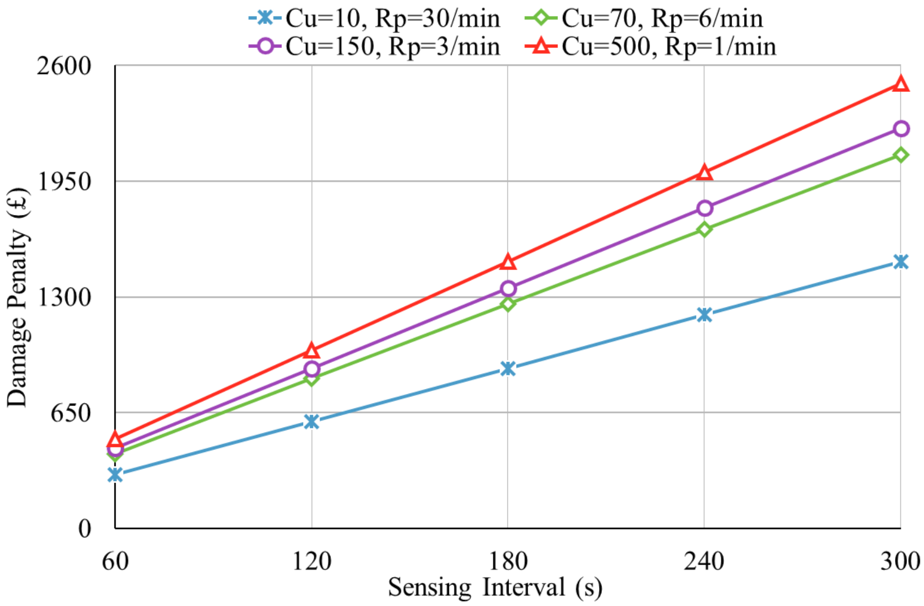


Figure 4.9: Damage Penalty with respect to various Sensing Intervals

present an example,the damage penalty is recorded when the unit cost of production is £10 and the rate of production reaches 30 *products per minute*. Both types of costs are comparable with each other in the start when sensing interval is around *1 min*. It is easy to understand from Figure 4.10 that overall cost goes on increasing with increase in sensing interval but the proportion of both costs keeps on changing against each other. Initially, the proportion of battery cost is 44% in comparison to overall cost that goes down to 3% of the overall cost when the LoRa monitoring nodes reaches *5 min* of sensing interval. On the other hand, damage penalty is doubled after every minute of increment to the sensing interval starting from £300 (when sensing interval is *1 min*) to £1500 if the sensing interval is stretched to *5 min*.

4.6.2 LoRaWAN in industrial monitoring scenarios with energy harvesting capabilities

The evaluation of LoRaWAN for industrial monitoring applications has been presented throughout the last sub-section where the monitoring nodes are assumed to be only battery powered. Sensing interval plays significant role in duty-cycling the monitoring nodes on the top of regional regulations to help them achieve optimum battery life. It is sometimes challenging tuning the sensing interval as it simultaneously involves two

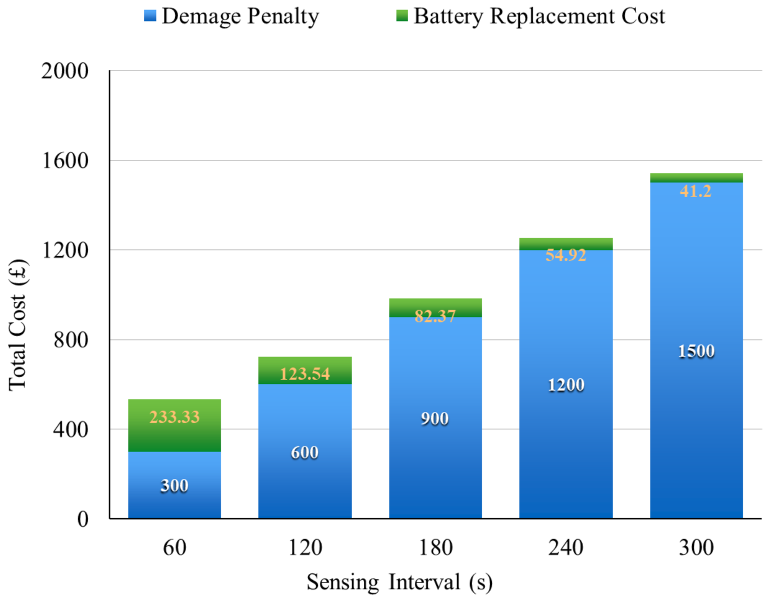


Figure 4.10: Total Cost summarizing Damage Penalty and Battery Replacement Cost when $C_u = \pounds 10, R_p = 30/min$

important but conflicting costs (discussed above in the last sub-section). Industrial potential for renewable energy has already been exploited by the research community [214, 215] and can dramatically come into play in two ways. *First*, due to the presence of energy harvested from the industrial environment, LoRa monitoring nodes can be fed by newly harvested energy minimizing the battery powered operation that would consequently prolong their life time. *Second*, thanks to the energy scavenging capabilities in industrial environment, sensing interval appears to be flexible and can be contracted as per the relaxation in energy quota without bothering about the life time of batteries. That would result minimizing the overall cost of the system along with production efficiency enhancement being the ultimate target of the administration of a smart industry. This section highlights the benefits of exploiting the harvesting potential in terms of extended battery life and flexible sensing interval and provides insight of how LoRaWAN performs far better in the presence of harvested energy as compared to the evaluations drawn in the previous sub-section.

4.6.2.1 Prolonging the Battery Life

Battery life with Energy harvesting: Battery life is the first milestone that can be extended taking energy harvesting into account within industrial environment. Average battery life is reevaluated in the presence of harvested energy and comparison with non-energy harvesting environment can be seen in Figure 4.11 against different sensing intervals.

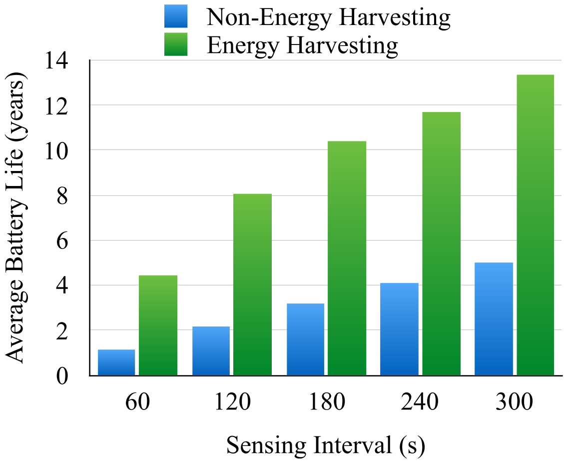


Figure 4.11: Average battery life comparison for energy harvesting and non-energy harvesting industrial scenarios employing LoRaWAN

Although the battery replacement cost and the damage penalty both are critical, however, in an attempt to cut down the one, the other may tend to go higher and vice versa in non-energy harvesting environment. On the other hand, the harvesting potential within a smart industry can dramatically make the difference as shown in Figure. 4.11 where the surplus amount of energy is capable to prolong the battery life many folds as we move along the sensing interval from 1 *min* to 5 *min*. The new battery life would obviously be contributing towards cutting down the battery replacement costs as depicted in Figure. 4.12. It can be observed that even in case of shortest sensing interval of a minute, the battery life can be extended many folds and can reach over 4 years when utilizing harvested energy without changing the sensing interval.

Battery replacement cost with energy harvesting: The battery replacement cost can be maintained as low as just over £13 beyond the sensing interval over 3

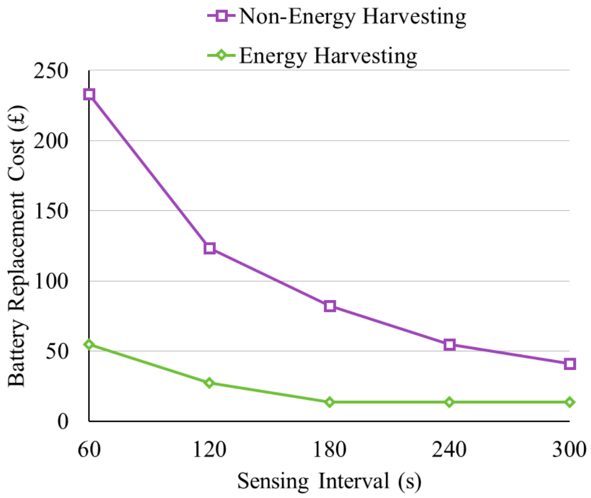


Figure 4.12: Comparison of battery replacement cost when exploiting energy harvesting sources in industrial environment

min compared to non-energy harvesting scenario where this cost starts from £41 and reaches over £80 in case of 3 *min* interval. The battery replacement cost goes on increasing when we go on shrinking the sensing interval because more number of battery replacement cycles are needed when the monitoring nodes wake up more frequently (e.g., in case of 1*min* sensing interval). Similarly, replacement cost does not go beyond £50 in energy harvesting scenario even if we sense every minute as compared to non-energy harvesting scenario where the replacement cost is recorded over £230 for the shortest interval of 1 *min*.

4.6.2.2 Contracting the Sensing Interval

Rate of sensing interval contraction: As mentioned in section 4.6.2, the flexibility in the sensing interval can also be achieved as an added advantage in addition to prolonging the battery life of monitoring nodes employing available harvesting potential within a smart industry. This flexibility enables shortening the sensing interval without compromising on the existing lifetime on monitoring nodes as demanded by several product lines with higher unit cost of product. Figure 4.13 demonstrate the rate at which sensing interval can be reduced in the presence of renewable energy. Here, it is worth mentioning that the rate of interval contraction ranges from 14% to 70% when we move from 1 *min* to 5 *min* sensing interval based on the amount of newly harvested energy available to the system. It implies that, a 5 *min* preset sensing interval for an IIoT application can be reduced to as short as 1.5 *min* whenever needed to reduce the long damage interval causing higher damage penalty.

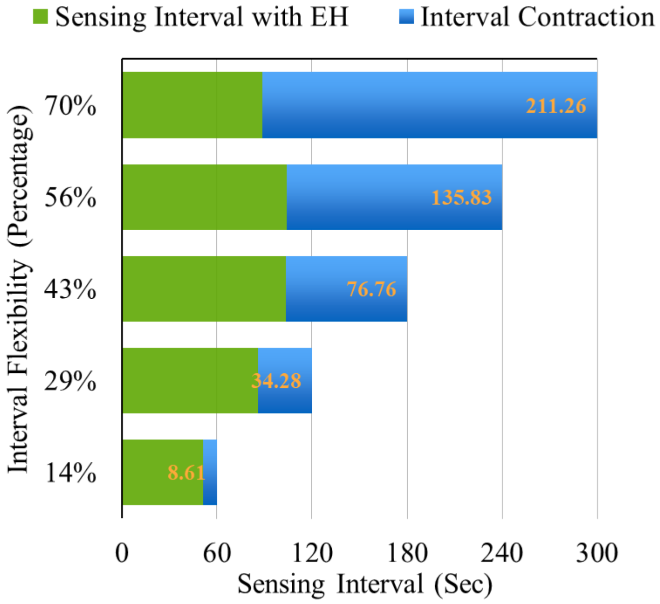


Figure 4.13: Sensing interval flexibility and the rate of interval contraction when exploiting energy harvesting sources in industrial environment

Damage penalty with energy harvesting: The industries with a significantly higher unit cost of production, C_{unit}, may consider saving on the damage penalty as compared to the battery replacement costs. The expert systems within these industries need frequent data collection for generating more updated alerts aiming at reporting the anomaly as early as possible. Having this in mind, a new sensing interval can also be derived instead of prolonging the battery life in compliance with the extra energy quota available through harvested energy. This new sensing interval is derived keeping in view the rate of sensing interval presented in Figure 4.13. Here, it is important to note that the rate of contraction gets higher as we move across the greater sensing intervals. This way, it is possible to confine the damage penalty up to just over thousand pounds beyond the sensing interval of 85s (previously, 120s) even in the most expensive category (where, $C_{unit} = \pounds 500$) as seen in Figure. 4.14. It can further be reduced up to 50% in an industry with low C_{unit}.

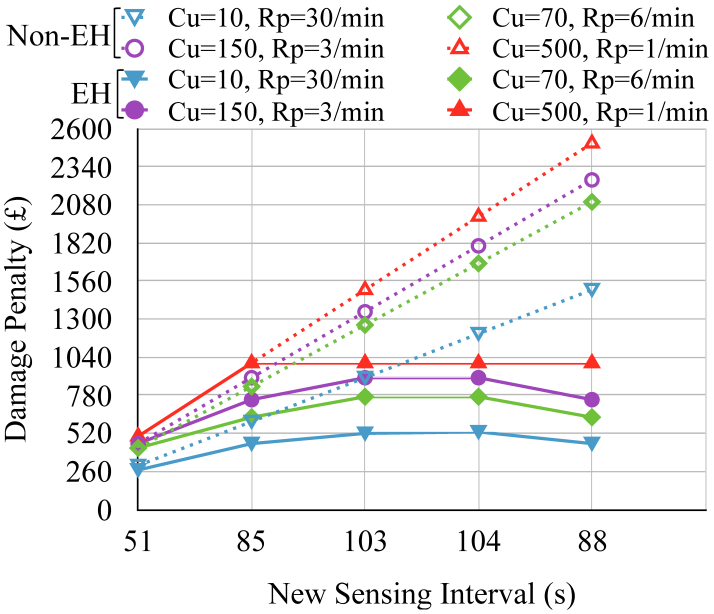


Figure 4.14: Comparison of Damage Penalty against new sensing intervals when exploiting energy harvesting sources in industrial environment

Aggregate costs with energy harvesting: Figure. 4.15 exhibits the overall cost picture where the aggregate of both costs (i.e., damage penalty and battery replacement cost) is compared with non-energy harvesting scenario in Figure 4.10. Figure. 4.15 shows the rate of interval contraction and the impact of contracting the sensing interval on the overall cost picture. It argues that no linear increase in the overall cost picture is evident moving along the sensing interval as compared to non-energy harvesting environment where the total cost tends to go on continuous increase with the increase in sensing interval. Interestingly, the contraction rate goes on so higher that the overall cost starts going down. The right most bar of Figure. 4.15 depicts that the aggregated costs recorded on $\Delta T_{sense} = 6\ min$ are even better (i.e. lower) than the aggregate costs recorded on $\Delta T_{sense} = 1\ min$ which justifies the choice of fairly long sensing interval.

4.6.2.3 Carbon emission savings analysis of LoRa nodes

Due to a higher incline in the global warming curve, serious efforts have been put in place by various segments of the society to de-carbonize the environment by fairly reducing the carbon footprints. The smart industries are also well on their way towards green industrial revolution by taking a range of measures to reduce carbon footprints

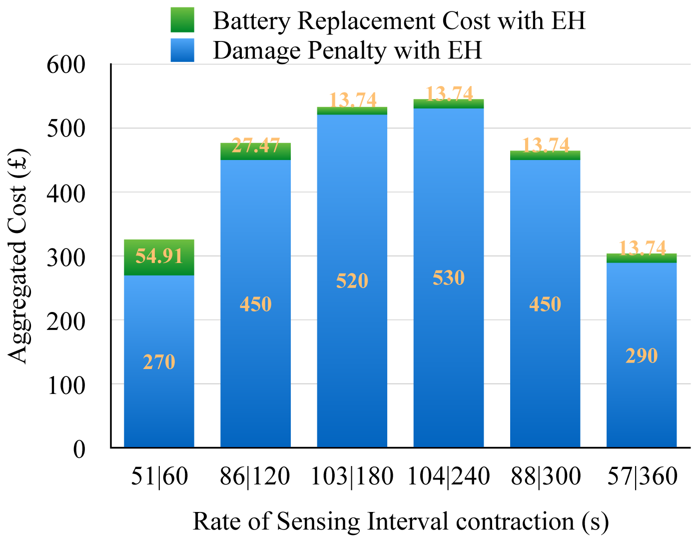
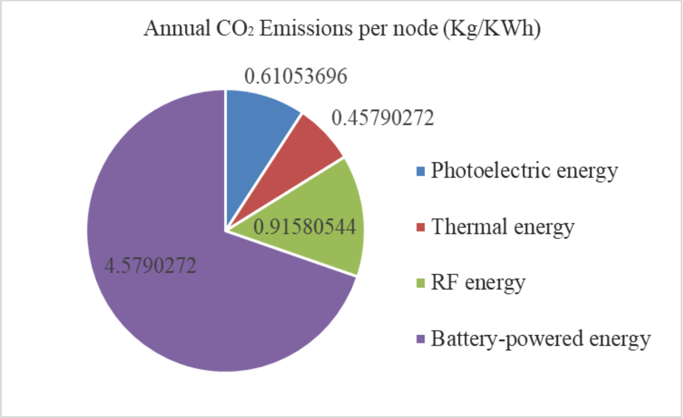


Figure 4.15: Aggregate cost in energy harvesting environment against the rate of sensing interval contraction

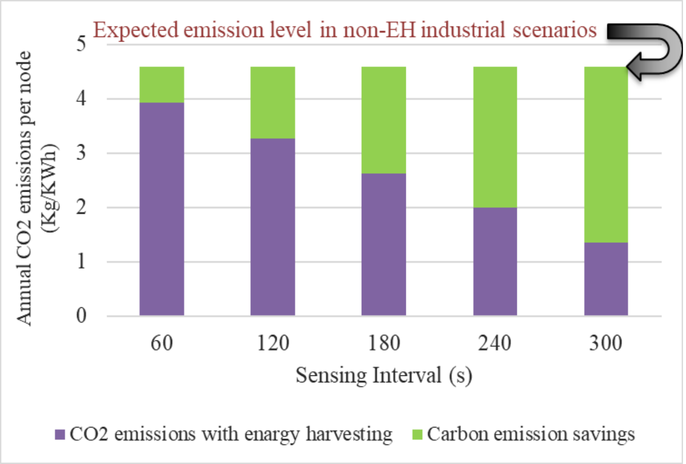
from different industrial processes. The employment of renewable energy sources not only offers industrial cost savings (discussed throughout the last section) but also contributes to fairly reduce the extent of carbon footprint caused by the conventional power generation.

Despite the green energy solutions, it is important to note that each kind of renewable energy source is associated with a certain amount of carbon per KWh of generation. By distrubuting these carbon emissions on the lifetime of the system, we can consider an amount of carbon associated with each type of renewable energy source as $15g/KWh$, $20g/KWh$, and $30g/KWh$ for thermoelectric, photoelectric, and RF energy respectively[63, 216] as compared to the CO_2 emission of fully battery powered monitoring devices as $150g/KWh$[217]. Let $CO_2^{batt.}$, CO_2^{TE}, CO_2^{PE}, and CO_2^{RF} are the carbon emissions associated with fully battery-powered, thermoelectric, photoelectric, and RF energy respectively and $E_{year} = V \cdot I \cdot 24 \cdot 365$, then by multiplying the carbon footprint associated with a renewable energy source to E_{year} yields an annual carbon emission of corresponding energy source. Figure 4.16(a) provides a comparison of the annual carbon emissions per node when a LoRa monitoring node is powered by aforementioned harvesting sources compared with fully battery-powered solution.

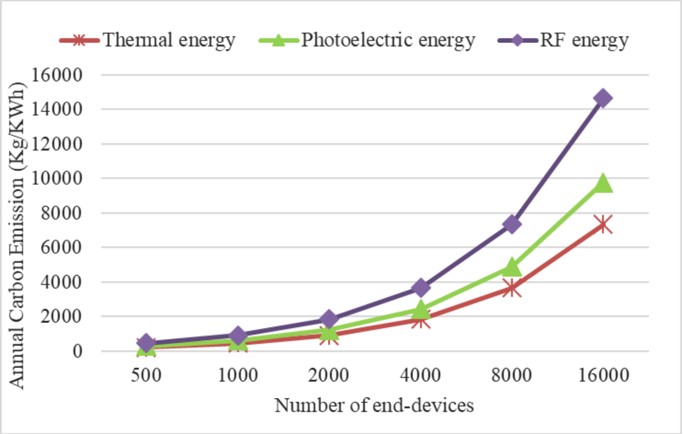
Similarly, the annual carbon emission savings per LoRa monitoring node can also be evaluated by subtracting the annual CO_2 emission in the presence of energy har-



(a) Comparison of annual carbon emissions per node for different energy harvesting sources



(b) Annual carbon emission savings per node against different sensing intervals



(c) Annual carbon emissions with different harvesting sources against number of end-devices

Figure 4.16: Carbon foorprint analysis in the presence of different energy harvesting technologies within industrial environment

vesting sources from the expected carbon emission in fully battery powered solution (i.e., $4.58Kg/KWh$). It can be expressed as:

$$CO_2^{savings} = E_{year} \cdot (CO_2^{batt.}) - (CO_2^{TE} + CO_2^{PE} + CO_2^{RF}) \tag{4.17}$$

Figure 4.16(b) presents the annual CO_2 emission savings per LoRa node against the sensing interval. It can be seen that the longer the sensing interval of LoRa monitoring nodes the greater the savings on carbon emissions. It is significant to note from Figure 4.16(b) that we are able to save up to $3.22Kg/KWh$ per LoRa node annually on the sensing interval of $5m$ that accounts for tons of annual carbon emission savings for a large scale network. Indeed, there may be thousands of end-devices spread across an industrial environment depending upon the use-case requirements. Figure 4.16(c) throws light on the annual emission savings in large scale LoRa network deployments for a smart industry where up to several thousands end-devices might be covered by each LoRa gateway. It can be concluded that even a medium size of LoRa network deployment with energy harvesting devices may save several tons of carbon emissions annually which is quite encouraging for the industrial administrations to consider energy harvesting LoRa deployments to actually realize the dream of green industrial revolution.

4.7 Summary

The work first presents a model to evaluate the energy consumption hence, estimating the battery life of LoRaWAN monitoring devices in an industrial environment. It then proposes to exploit several renewable energy resources available in a smart industry and highlights the impact of this harvesting potential on the battery replacement cost and damage penalty. Furthermore, it throws light to get an insight of the interesting cost relationship for battery replacement and damage penalty in industry 4.0, and how both of these costs reciprocate each other in a smart factory where the damage penalty can sometimes be huge as compared to battery replacement cost. Moreover, the results first evaluate several aspects of LoRaWAN in a plain industrial environment and then a comprehensive comparison is provided for the same set in energy harvesting industrial environment.

The work highlights the following important aspects. First, the damage penalty remains higher than battery replacement cost for longer sensing intervals and both the costs tend to equalize around the sensing interval of $1min$. Second, the battery replacement costs are decreased because of prolonged battery life in the presence of harvested energy without affecting the sensing interval. Third, renewable energy being added to the system also provides the flexibility to contract the sensing interval to achieve more updated alerts. Fourth, both the costs can be cut-down in case of harvested energy to get the least aggregate cost as compared to non-energy harvesting environment. Fifth, the overall cost no more shows a linear increase in the presence of harvested energy and tends to decline beyond the sensing interval of $4min$. It falls down to as lower as £300 especially on sensing interval of $6min$, even lower than the total cost noted on $1min$ sensing interval.

5

Conclusions and Future Research Directions

The last decade has been the witness of the explosion of the IoT paradigm. Billions of smart and tiny devices are hitting the market, equipped with sensing and actuating capabilities and provide the possibility to interact with them over the big Internet. It paves the way to a variety of innovative applications in different contexts, such as environmental monitoring, smart building, home automation, health care, logistics and energy management, to name a few. Moreover, the innovations and step-ups they provide, especially in industrial applications, is enabling a wide set of advanced services, indicated as the forth industrial revolution, Industry 4.0, that will leverage on the new specific paradigm of the Industrial Internet of Things (IIoT). Major leading companies of the sector are also expecting an enormous growth of the technology, up to an ambitious threshold of 50 billion of smart connected devices in 2020.

Throughout the PhD, the focus has been on the energy issues faced by the IoT deployments, in general, and LP-WAN, in specific, raised by this gigantic growth of the IoT devices, and due to its unfalsifiable importance to meet several, but conflicting, design objectives. As a result of general consensus developed across the research community, it is inevitable to explore the new ways of energy generation to fulfill this burning demand of energy for the next generation low power motes targeting a wide geographical area. Here, it is worth mentioning some most important lessons learned throughout this study of exploring energy harvesting approaches in the context of WSN and LP-WAN.

With reference to studying energy harvesting MAC protocols for sensor networks, we remark that each of the EH-MAC protocols explored throughout Chapter 2, refers to a single harvesting technique due to unique set of complexities and trade-offs involved in each technique. Hence, energy model for each harvesting technique is protocol specific. Moreover, it is the need of time to establish a common simulation framework to validate energy harvesting MAC protocols with similar protocols instead of comparing their performance with plain MAC protocols. Furthermore, very few EH-MAC protocols are tested on practical implementations which can severely influence the performance of different metrics. There is a thin line between low energy utilization and optimum performance level that should be considered while designing EH-MAC protocols. Lastly, Among the EH-MAC protocols analyzed, only some of them can be considered for different IoT use-cases.

Taking a step ahead, a feasibility of cable-less LoRaWAN deployments was investigated in Chapter 3 that is fed by the renewable energy acquired from solar panels designed in line with the energy requirements of these dual radio gateways, serving a mix of M2M communication at peak load, leveraging the different combinations of fron-end chipset and backhaul wireless technologies. This kind of solution is especially useful in the following three use-cases. First, where the direct grid connectivity is not feasible because of odd installation spot. Second, where the grid connectivity limits the performance (e.g., in terms of achieving optimum radio coverage) of LoRa gateways. Third, the service providers are intended to cut-down the operating costs. These benefits would not only enable the existing private and public LoRaWAN infrastructures to upgrade themselves, but it would also be able to support new LoRaWAN business use-cases, including low power network operations, coverage and capacity enhancement, rapid network expansion, and lower deployment costs and time to market for MNOs.

Studying the most energy exhaustive use-case of industry 4.0., it is possible to remark that a minimum sensing interval of 1 m is possible keeping in view the regional duty-cycle restrictions of 1% in most of the ISM bands. Thanks to the proposed model in an industry 4.0 environment, another important consideration is to evaluate the energy consumption for industrial monitoring LoRa motes and analyze the trade-off between battery replacement costs and the cost due to the production of damaged products (i.e., damage plenty) in case an anomaly is detected.Moreover, it investigates the potential of energy harvesting in industry 4.0 and highlight that by employing the additional energy quota provided, either the battery life of LoRa monitoring nodes can be prolonged (i.e., up to many folds) or there is a possibility to shorten the sensing interval (i.e., sense and transmit more frequently) for more updated alerts at the expert system. This can avoid huge financial losses by timely reporting an anomaly soon after its occurrence.

There may be a variety of correlated research orientations we are planning to extend our research activities towards. The problem discussed in Chapter 3 can be extended towards different interesting directions. For example, we are planning to construct a generic model to find out the best suited LP-WAN candidate for a particular use-case evaluating the some key requirements (such as, radio coverage, bit-rate, and latency). we are also planning a thorough investigation on the CAPEX and OPEX of each LP-WAN solution and switching cost from one LP-WAN option to another.

Moreover, the problem covered in Chapter 4 can also be extended in several directions. The problem can be formulated in terms of optimization problem where maximization the lifetime of LoRa monitoring nodes may be an objective function and both the costs (i.e., battery replacement costs and damage penalty) can be the constraints. Alternatively, minimizing one of the costs can also be the objective function depending upon the type of industrial application.

Finally, the work can be extended towards designing a generic low cost LP-WAN gateway that is capable enough to relay the communication across multiple LP-WAN technologies as with the enormous growth of IoT devices manufactured by different vendors, the integration of these devices across the technologies to achieve seamless connectivity and coherent operation is the need of time that should be a future topic for the researchers working in this area.

References

[1] J. Gubbi, R. Buyya, S. Marusic, and M. Palaniswami, "Internet of things (iot): A vision, architectural elements, and future directions," *Future generation computer systems*, vol. 29, no. 7, pp. 1645–1660, 2013. 1

[2] R. H. Weber and R. Weber, *Internet of things.* Springer, 2010, vol. 12.

[3] L. Atzori, A. Iera, and G. Morabito, "The internet of things: A survey," *Computer networks*, vol. 54, no. 15, pp. 2787–2805, 2010. 1

[4] O. Hersent, D. Boswarthick, and O. Elloumi, *The Internet of Things: Key Applications and Protocols.* Wiley, 2012. 1

[5] L. A. Grieco, A. Rizzo, S. Colucci, S. the, G. Piro, D. Di Paola, and G. Boggia, "IoT-aided robotics applications: technological implications, target domains and open issues," vol. 54, December 2014. 1

[6] D. Evans, "The internet of things, how the next evolution of the internet is changing everything," Cisco Internet Business Solutions Group (IBSG). White paper, Apr. 2011. 2

[7] Ericsson, "More than 50 billion connected devices," Ericsson White Paper, Feb. 2011.

[8] B. Emmerson, "M2M: the Internet of 50 billion devices," *Huawei Win-Win Magazine Journal*, no. 4, pp. 19–22, Jan. 2010. 2

[9] M. Palattella, N. Accettura, X. Vilajosana, T. Watteyne, L. Grieco, G. Boggia, and M. Dohler, "Standardized Protocol Stack for the Internet of (Important) Things," *IEEE Commun. Surveys Tuts*, 2012. 2

[10] D. Miorandi, S. Sicari, F. D. Pellegrini, and I. Chlamtac, "Internet of Things: Vision, Applications & Research Challenges," *Ad Hoc Networks*, 2012.

[11] L. Atzori, A. Iera, and G. Morabito, "The Internet of Things: A survey," *Computer Networks*, vol. 54, no. 15, pp. 2787–2805, Oct. 2010. 2

[12] K. Ashton, "That Internet of Things Thing," *RFID Journal*, 2009. 2

[13] D. Singh, G. Tripathi, and A. J. Jara, "A survey of internet-of-things: Future vision, architecture, challenges and services," in *Internet of things (WF-IoT), 2014 IEEE world forum on.* IEEE, 2014, pp. 287–292. 3

[14] M. C. Bor, U. Roedig, T. Voigt, and J. M. Alonso, "Do lora low-power wide-area networks scale?" in *Proceedings of the 19th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems.* ACM, 2016, pp. 59–67. 5, 25

[15] U. Raza, P. Kulkarni, and M. Sooriyabandara, "Low power wide area networks: An overview," *IEEE Communications Surveys Tutorials*, vol. PP, no. 99, pp. 1–19, 2017. 5, 21, 22, 23, 26, 44, 130, 131, 132, 137

[16] B. Lee and Y. Hyoseok, "Low power wide area network," Nov. 24 2016, uS Patent App. 15/093,969. 5

[17] M. Pulpito, P. Fornarelli, C. Pomo, P. Boccadoro, and L. A. Grieco, "On fast prototyping lorawan: a cheap and open platform for daily experiments," *IET Wireless Sensor Systems*, vol. 8, no. 5, pp. 237–245, 2018. 6, 12

[18] X. Xiong, K. Zheng, R. Xu, W. Xiang, and P. Chatzimisios, "Low power wide area machine-to-machine networks: key techniques and prototype," *IEEE Communications Magazine*, vol. 53, no. 9, pp. 64–71, 2015. 6, 28

[19] A. Group *et al.*, "Alarmnet introduces control channel cellular for commercial fire/burglary applications, ademco group (press release), aug. 31, 1999," 2009. 9

[20] ARDIS, "Wide Area Wireless Network," 2018, accessed: 18 December 2018. [Online]. Available: http://www.mobileinfo.com/Wireless_Networks/wireless_wan_ardis_.htm 9

[21] B. Nath, F. Reynolds, and R. Want, "Rfid technology and applications," *IEEE Pervasive Computing*, no. 1, pp. 22–24, 2006. 10

[22] V. Coskun, B. Ozdenizci, and K. Ok, "A survey on near field communication (nfc) technology," *Wireless personal communications*, vol. 71, no. 3, pp. 2259–2294, 2013. 10

[23] P. Bhagwat, "Bluetooth: technology for short-range wireless apps," *IEEE Internet Computing*, vol. 5, no. 3, pp. 96–103, 2001. 10

[24] R. Heydon, *Bluetooth low energy: the developer's handbook.* Prentice Hall Upper Saddle River, NJ, 2013, vol. 1. 10

[25] D. Wang, J.-r. Zhang, Y. WEI, C.-x. CAO, and Z. TANG, "Building wireless sensor networks (wsns) by zigbee technology [j]," *Journal of Chongqing university (natural science edition)*, vol. 8, p. 023, 2006. 10

[26] A. I. Al-Alawi, "Wifi technology: Future market challenges and opportunities," *Journal of computer Science*, vol. 2, no. 1, pp. 13–18, 2006. 10

[27] T. Halonen, J. Romero, and J. Melero, *GSM, GPRS and EDGE performance: evolution towards 3G/UMTS.* John Wiley & Sons, 2004. 11

[28] E. Dahlman, S. Parkvall, and J. Skold, *4G: LTE/LTE-advanced for mobile broadband.* Academic press, 2013. 11

[29] J. Gozalvez, "New 3gpp standard for iot [mobile radio]," *IEEE Vehicular Technology Magazine*, vol. 11, no. 1, pp. 14–20, 2016. 11

[30] Y.-P. E. Wang, X. Lin, A. Adhikary, A. Grovlen, Y. Sui, Y. Blankenship, J. Bergman, and H. S. Razaghi, "A primer on 3gpp narrowband internet of things," *IEEE Communications Magazine*, vol. 55, no. 3, pp. 117–123, 2017. 11

[31] S. Persia and L. Rea, "Next generation m2m cellular networks: Lte-mtc and nb-iot capacity analysis for smart grids applications," in *AEIT International Annual Conference (AEIT), 2016.* IEEE, 2016, pp. 1–6. 11

[32] G. Auer, V. Giannini, C. Desset, I. Godor, P. Skillermark, M. Olsson, M. A. Imran, D. Sabella, M. J. Gonzalez, O. Blume *et al.*, "How much energy is needed to run a wireless network?" *IEEE Wireless Communications*, vol. 18, no. 5, 2011. 12

[33] S. Dixit and R. Prasad, *Technologies for home networking.* John Wiley & Sons, 2007. 12

[34] A. Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi, "Internet of things for smart cities," *IEEE Internet of Things journal*, vol. 1, no. 1, pp. 22–32, 2014. 14

[35] K. Su, J. Li, and H. Fu, "Smart city and the applications," in *Electronics, Communications and Control (ICECC), 2011 International Conference on.* IEEE, 2011, pp. 1028–1031.

[36] J. Jin, J. Gubbi, S. Marusic, and M. Palaniswami, "An information framework for creating a smart city through internet of things," *IEEE Internet of Things journal*, vol. 1, no. 2, pp. 112–121, 2014.

[37] A. Gaur, B. Scotney, G. Parr, and S. McClean, "Smart city architecture and its applications based on iot," *Procedia computer science*, vol. 52, pp. 1089–1094, 2015. 14

[38] F. Shrouf, J. Ordieres, and G. Miragliotta, "Smart factories in industry 4.0: A review of the concept and of energy management approached in production based on the internet of things paradigm," in *Industrial Engineering and Engineering Management (IEEM), 2014 IEEE International Conference on.* IEEE, 2014, pp. 697–701. 15

[39] M. Wollschlaeger, T. Sauter, and J. Jasperneite, "The future of industrial communication: Automation networks in the era of the internet of things and industry 4.0," *IEEE Industrial Electronics Magazine*, vol. 11, no. 1, pp. 17–27, 2017.

[40] A. Gilchrist, *Industry 4.0: the industrial internet of things.* Apress, 2016.

[41] H. H. R. Sherazi, M. A. Imran, G. Boggia, and L. A. Grieco, "Energy harvesting in lorawan: A cost analysis for the industry 4.0," *IEEE Communications Letters*, 2018. 15

[42] N. Dlodlo and J. Kalezhi, "The internet of things in agriculture for sustainable rural development," in *Emerging Trends in Networks and Computer Communications (ETNCC), 2015 International Conference on*. IEEE, 2015, pp. 13–18. 17

[43] L. Daoliang, "Internet of things and wisdom agriculture [j]," *Agricultural engineering*, vol. 1, no. 003, 2012. 17

[44] S. Li, "Application of the internet of things technology in precision agriculture irrigation systems," in *Computer Science & Service System (CSSS), 2012 International Conference on*. IEEE, 2012, pp. 1009–1013. 17

[45] J. Ye, B. Chen, Q. Liu, and Y. Fang, "A precision agriculture management system based on internet of things and webgis," in *Geoinformatics (GEOINFORMATICS), 2013 21st International Conference on*. IEEE, 2013, pp. 1–5. 17

[46] S. Kadge, H. A. Chaudhary, A. Q. Zilani, and Y. Jain, "Asset management based on internet of things," *International Journal of Computer Applications*, vol. 137, no. 10, 2016. 18

[47] O. Vermesan and P. Friess, *Internet of things: converging technologies for smart environments and integrated ecosystems*. River Publishers, 2013. 18

[48] L. Catarinucci, D. De Donno, L. Mainetti, L. Palano, L. Patrono, M. L. Stefanizzi, and L. Tarricone, "An iot-aware architecture for smart healthcare systems," *IEEE Internet of Things Journal*, vol. 2, no. 6, pp. 515–526, 2015. 19, 52

[49] F. Fernandez and G. C. Pallis, "Opportunities and challenges of the internet of things for healthcare: Systems engineering perspective," in *Wireless Mobile Communication and Healthcare (Mobihealth), 2014 EAI 4th International Conference on*. IEEE, 2014, pp. 263–266. 19

[50] D. Patel, "Low power wide area networks (lpwan): Technology review and experimental study on mobility effect," 2018. 21

[51] J. Petäjäjärvi, K. Mikhaylov, A. Roivainen, T. Hänninen, and M. Pettissalo, "On the coverage of LPWANs: Range evaluation and channel attenuation model for LoRa technology," in *2015 14th International Conference on ITS Telecommunications, ITST 2015*, 2016, pp. 55–59. 21, 22, 98

[52] M. Anteur, V. Deslandes, N. Thomas, and A.-L. Beylot, "Ultra narrow band technique for low power wide area communications," in *Global Communications Conference (GLOBECOM), 2015 IEEE*. IEEE, 2015, pp. 1–6. 22

[53] A. Augustin, J. Yi, T. Clausen, and W. M. Townsley, "A Study of LoRa: Long Range & Low Power Networks for the Internet of Things," *Sensors*, vol. 16, no. 9, p. 1466, 2016. 22, 37

[54] K. Mikhaylov, J. Petäjäjärvi, and T. Hänninen, "Analysis of Capacity and Scalability of the LoRa Low Power Wide Area Network Technology," in *proceedings of Europaen Wireless*, May 2016, pp. 119–124. 22, 25, 98, 105

[55] D. Patel and M. Won, "Experimental study on low power wide area networks (lpwan) for mobile internet of things," in *Vehicular Technology Conference (VTC Spring), 2017 IEEE 85th*. IEEE, 2017, pp. 1–5. 23

[56] P. Neumann, J. Montavont, and T. Noël, "Indoor deployment of low-power wide area networks (lpwan): A lorawan case study," in *Wireless and Mobile Computing, Networking and Communications (WiMob), 2016 IEEE 12th International Conference on*. IEEE, 2016, pp. 1–8. 23

[57] P. Thubert, A. Pelov, and S. Krishnan, "Low-power wide-area networks at the ietf," *IEEE Communications Standards Magazine*, vol. 1, no. 1, pp. 76–79, 2017. 23

[58] K. E. Nolan, W. Guibene, and M. Y. Kelly, "An evaluation of low power wide area network technologies for the internet of things," in *Wireless Communications and Mobile Computing Conference (IWCMC), 2016 International*. IEEE, 2016, pp. 439–444. 24, 132, 133

[59] F. Adelantado, X. Vilajosana, P. Tuset-Peiro, B. Martinez, J. Melia-Segui, and T. Watteyne, "Understanding the limits of lorawan," *IEEE Communications Magazine*, vol. 55, no. 9, pp. 34–40, 2017. 24, 42, 43

[60] J.-P. Bardyn, T. Melly, O. Seller, and N. Sornin, “Iot: The era of lpwan is starting now,” in *European Solid-State Circuits Conference, ESSCIRC Conference 2016: 42nd.* IEEE, 2016, pp. 25–30. 24

[61] H. Al-Kashoash and A. H. Kemp, “Comparison of 6lowpan and lpwan for the internet of things,” *Australian Journal of Electrical and Electronics Engineering*, vol. 13, no. 4, pp. 268–274, 2016. 24

[62] C. Pham, F. Ferrero, M. Diop, L. Lizzi, O. Dieng, and O. Thiaré, “Low-cost antenna technology for lpwan iot in rural applications,” in *Advances in Sensors and Interfaces (IWASI), 2017 7th IEEE International Workshop on.* IEEE, 2017, pp. 121–126. 25, 26, 33

[63] H. H. R. Sherazi, G. Piro, L. A. Grieco, and G. Boggia, “When renewable energy meets lora: A feasibility analysis on cable-less deployments,” *IEEE Internet of Things Journal*, 2018. 27, 161

[64] K. Mekki, E. Bajic, F. Chaxel, and F. Meyer, “A comparative study of lpwan technologies for large-scale iot deployment,” *ICT Express*, 2018. 37

[65] M. R. Palattella, M. Dohler, A. Grieco, G. Rizzo, J. Torsner, T. Engel, and L. Ladid, “Internet of things in the 5g era: Enablers, architecture, and business models,” *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 3, pp. 510–527, March 2016. 37

[66] N. Sornin, M. Luis, T. Eirich, T. Kramp, and O. Hersent, “LoRaWAN Specification v.1.0,” pp. 1–82, 2015. [Online]. Available: https://www.lora-alliance.org/portals/0/specs/LoRaWANSpecification1R0.pdf 37, 38, 39

[67] N. Sornin, “LoRaWAN Specification Development,” LoRa Alliance, Tech. Rep., 2017. 37

[68] Semtech Inc., “LoRa Use Cases,” 2017, accessed: 12 April 2017. [Online]. Available: http://www.semtech.com/wireless-rf/internet-of-things/lora-applications/briefs 38

[69] S.-K. Park, K.-i. Hwang, H.-S. Kim, and B.-S. Shim, “Challenges and experiment with lorawan,” in *Advanced Multimedia and Ubiquitous Engineering.* Springer, 2017, pp. 269–276. 41

[70] P. San Cheong, J. Bergs, C. Hawinkel, and J. Famaey, “Comparison of lorawan classes and their power consumption,” in *Communications and Vehicular Technology (SCVT), 2017 IEEE Symposium on.* IEEE, 2017, pp. 1–6. 41

[71] D. Bankov, E. Khorov, and A. Lyakhov, “On the limits of lorawan channel access,” in *2016 International Conference on Engineering and Telecommunication (EnT)*, Nov 2016, pp. 10–14. 42, 97, 98, 99

[72] D. F. Carvalho, P. Ferrari, A. Flammini, and E. Sisinni, “A test bench for evaluating communication delays in lorawan applications,” in *2018 Workshop on Metrology for Industry 4.0 and IoT*, April 2018, pp. 248–253. 45

[73] H. H. R. Sherazi, L. A. Grieco, and G. Boggia, “A comprehensive review on energy harvesting mac protocols in wsns: Challenges and tradeoffs,” *Ad Hoc Networks*, vol. 71, pp. 117 – 134, 2018. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1570870518300040 45, 48

[74] M. Li and H.-J. Lin, “Design and implementation of smart home control systems based on wireless sensor networks and power line communications,” pp. 4430–4442, 2015. 52

[75] J.-S. Jeong, O. Han, and Y.-Y. You, “A design characteristics of smart healthcare system as the iot application,” *Indian Journal of Science and Technology*, vol. 9, no. 37, 2016. 52

[76] K. Nellore and G. P. Hancke, “A survey on urban traffic management system using wireless sensor networks,” *Sensors*, vol. 16, no. 2, p. 157, 2016. 52

[77] C. Lung, S. Sabou, and A. Buchman, “Wireless sensor networks as part of emergency situations management system,” in *Design and Technology in Electronic Packaging (SIITME), 2016 IEEE 22nd International Symposium for.* IEEE, 2016, pp. 240–243. 52, 56

[78] D. Antolín, N. Medrano, B. Calvo, and F. Pérez, "A wearable wireless sensor network for indoor smart environment monitoring in safety applications," *Sensors*, vol. 17, no. 2, p. 365, 2017. 52, 56

[79] H. M. A. Fahmy, "Wireless sensor networks," *Concepts, Applications, Experimenta*, 2016. 52

[80] V. Raghunathan, S. Ganeriwal, and M. Srivastava, "Emerging techniques for long lived wireless sensor networks," *IEEE Communications Magazine*, vol. 44, no. 4, pp. 108–114, 2006. 52, 64

[81] J. A. Khan, H. K. Qureshi, and A. Iqbal, "Energy management in wireless sensor networks: A survey," *Computers & Electrical Engineering*, vol. 41, pp. 159–176, 2015.

[82] Y. Liu, Y. Wang, H. Long, and H. Yang, "Lifetime-aware battery allocation for wireless sensor network under cost constraints," *IEICE transactions on communications*, vol. 95, no. 5, pp. 1651–1660, 2012. 52

[83] W. Ye, J. Heidemann, and D. Estrin, "An energy-efficient mac protocol for wireless sensor networks," in *INFOCOM 2002. Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, vol. 3. IEEE, 2002, pp. 1567–1576. 52

[84] J. Polastre, J. Hill, and D. Culler, "Versatile low power media access for wireless sensor networks," in *Proceedings of the 2nd international conference on Embedded networked sensor systems.* ACM, 2004, pp. 95–107. 52

[85] M. Buettner, G. V. Yee, E. Anderson, and R. Han, "X-mac: a short preamble mac protocol for duty-cycled wireless sensor networks," in *Proceedings of the 4th international conference on Embedded networked sensor systems.* ACM, 2006, pp. 307–320. 52

[86] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks," in *System sciences, 2000. Proceedings of the 33rd annual Hawaii international conference on.* IEEE, 2000, pp. 10–pp. 52

[87] C. Intanagonwiwat, R. Govindan, and D. Estrin, “Directed diffusion: A scalable and robust communication paradigm for sensor networks,” in *Proceedings of the 6th annual international conference on Mobile computing and networking.* ACM, 2000, pp. 56–67.

[88] P. Desnoyers, D. Ganesan, H. Li, M. Li, and P. J. Shenoy, “Presto: A predictive storage architecture for sensor networks.” in *HotOS*, vol. 5, 2005, pp. 12–15. 52

[89] S. Ganeriwal, I. Tsigkogiannis, H. Shim, V. Tsiatsis, M. B. Srivastava, and D. Ganesan, “Estimating clock uncertainty for efficient duty-cycling in sensor networks,” *IEEE/ACM transactions on Networking*, vol. 17, no. 3, pp. 843–856, 2009. 53

[90] P. Dutta, M. Grimmer, A. Arora, S. Bibyk, and D. Culler, “Design of a wireless sensor network platform for detecting rare, random, and ephemeral events,” in *Proceedings of the 4th international symposium on Information processing in sensor networks.* IEEE Press, 2005, p. 70. 53

[91] H. Liu, A. Chandra, and J. Srivastava, “esense: energy efficient stochastic sensing framework scheme for wireless sensor platforms,” in *Proceedings of the 5th international conference on Information processing in sensor networks.* ACM, 2006, pp. 235–242. 53

[92] O. Gnawali, K.-Y. Jang, J. Paek, M. Vieira, R. Govindan, B. Greenstein, A. Joki, D. Estrin, and E. Kohler, “The tenet architecture for tiered sensor networks,” in *Proceedings of the 4th international conference on Embedded networked sensor systems.* ACM, 2006, pp. 153–166. 53

[93] P. Kulkarni, D. Ganesan, P. Shenoy, and Q. Lu, “Senseye: a multi-tier camera sensor network,” in *Proceedings of the 13th annual ACM international conference on Multimedia.* ACM, 2005, pp. 229–238.

[94] P. Kulkarni, D. Ganesan, and P. Shenoy, “The case for multi–tier camera sensor networks,” in *Proceedings of the international workshop on Network and operating systems support for digital audio and video.* ACM, 2005, pp. 141–146. 53

[95] X. Wang, G. Xing, Y. Zhang, C. Lu, R. Pless, and C. Gill, "Integrated coverage and connectivity configuration in wireless sensor networks," in *Proceedings of the 1st international conference on Embedded networked sensor systems.* ACM, 2003, pp. 28–39. 53

[96] S. Kumar, T. H. Lai, and J. Balogh, "On k-coverage in a mostly sleeping sensor network," in *Proceedings of the 10th annual international conference on Mobile computing and networking.* ACM, 2004, pp. 144–158. 53

[97] S. Ulukus, A. Yener, E. Erkip, O. Simeone, M. Zorzi, P. Grover, and K. Huang, "Energy harvesting wireless communications: A review of recent advances," *IEEE Journal on Selected Areas in Communications*, vol. 33, no. 3, pp. 360–381, 2015. 53

[98] R. Ramya, G. Saravanakumar, and S. Ravi, "Energy harvesting in wireless sensor networks," in *Artificial Intelligence and Evolutionary Computations in Engineering Systems.* Springer, 2016, pp. 841–853.

[99] F. K. Shaikh and S. Zeadally, "Energy harvesting in wireless sensor networks: A comprehensive review," *Renewable and Sustainable Energy Reviews*, vol. 55, pp. 1041–1054, 2016. 53

[100] I. Demirkol, C. Ersoy, F. Alagoz *et al.*, "Mac protocols for wireless sensor networks: a survey," *IEEE Communications Magazine*, vol. 44, no. 4, pp. 115–121, 2006. 53

[101] R. Ramya, G. Saravanakumar, and S. Ravi, "Mac protocols for wireless sensor networks," *Indian Journal of Science and Technology*, vol. 8, no. 34, 2015.

[102] A. Bachir, M. Dohler, T. Watteyne, and K. K. Leung, "Mac essentials for wireless sensor networks," *IEEE Communications Surveys & Tutorials*, vol. 12, no. 2, pp. 222–248, 2010. 53, 64

[103] M. A. Yigitel, O. D. Incel, and C. Ersoy, "Qos-aware mac protocols for wireless sensor networks: A survey," *Computer Networks*, vol. 55, no. 8, pp. 1982–2004, 2011. 53, 64, 66

[104] P. Huang, L. Xiao, S. Soltani, M. W. Mutka, and N. Xi, “The evolution of mac protocols in wireless sensor networks: A survey,” *IEEE communications surveys & tutorials*, vol. 15, no. 1, pp. 101–120, 2013.

[105] E. Chukwuka and K. Arshad, “Energt efficient mac protocols for wireless sensor network: A survey,” *International Journal of Wireless & Mobile Networks*, vol. 4, no. 5, pp. 75–89, 2013.

[106] N. Trivedi, G. Kuamr, and T. Raikwar, “Survey on mac protocol for wireless sensor network,” *International Journal of Emerging Technology and Advanced, Engineering*, vol. 3, pp. 558–562, 2013.

[107] A. Kakria and T. C. Aseri, “A survey on asynchronous mac protocols in wireless sensor networks,” *International Journal of Computer Applications*, vol. 108, no. 9, 2014.

[108] F. Alfayez, M. Hammoudeh, and A. Abuarqoub, “A survey on mac protocols for duty-cycled wireless sensor networks,” *Procedia Computer Science*, vol. 73, pp. 482–489, 2015.

[109] A. Verma, M. Singh, J. P. Singh, and P. Kumar, “Survey of mac protocol for wireless sensor networks,” in *Advances in Computing and Communication Engineering (ICACCE), 2015 Second International Conference on.* IEEE, 2015, pp. 92–97. 53, 64, 66

[110] P. Ramezani and M. R. Pakravan, “Overview of mac protocols for energy harvesting wireless sensor networks,” in *Personal, Indoor, and Mobile Radio Communications (PIMRC), 2015 IEEE 26th Annual International Symposium on.* IEEE, 2015, pp. 2032–2037. 53

[111] S. Kosunalp, “Mac protocols for energy harvesting wireless sensor networks: Survey,” *ETRI journal*, vol. 37, no. 4, pp. 804–812, 2015. 53

[112] S. Beeby and N. White, *Energy harvesting for autonomous systems.* Artech House, 2010. 54

[113] J. A. Paradiso and T. Starner, “Energy scavenging for mobile and wireless electronics,” *IEEE Pervasive computing*, no. 1, pp. 18–27, 2005. 57, 62

[114] Z. Wan, Y. Tan, and C. Yuen, “Review on energy harvesting and energy management for sustainable wireless sensor networks,” in *Communication Technology (ICCT), 2011 IEEE 13th International Conference on.* IEEE, 2011, pp. 362–367. 57, 62

[115] Y. K. Tan and S. K. Panda, “Review of energy harvesting technologies for sustainable wsn,” in *Sustainable wireless sensor networks.* InTech, 2010. 58, 59, 60

[116] G. Zhou, L. Huang, W. Li, and Z. Zhu, “Harvesting ambient environmental energy for wireless sensor networks: a survey,” *Journal of Sensors*, vol. 2014, 2014. 59

[117] S. Roundy, P. K. Wright, and J. Rabaey, “A study of low level vibrations as a power source for wireless sensor nodes,” *Computer communications*, vol. 26, no. 11, pp. 1131–1144, 2003. 59

[118] S. Sudevalayam and P. Kulkarni, “Energy harvesting sensor nodes: Survey and implications,” *IEEE Communications Surveys & Tutorials*, vol. 13, no. 3, pp. 443–461, 2011. 59

[119] T. Zou, S. Lin, Q. Feng, and Y. Chen, “Energy-efficient control with harvesting predictions for solar-powered wireless sensor networks,” *Sensors*, vol. 16, no. 1, p. 53, 2016. 65

[120] B.-C. Lee and G.-S. Chung, “Low-frequency driven energy harvester with multipole magnetic structure,” *Journal of Mechanical Science and Technology*, vol. 29, no. 2, pp. 441–446, 2015. 59

[121] T. D. Hieu, B.-S. Kim *et al.*, “Stability-aware geographic routing in energy harvesting wireless sensor networks,” *Sensors*, vol. 16, no. 5, p. 696, 2016. 59

[122] K. Tashiro, H. Wakiwaka, S.-i. Inoue, and Y. Uchiyama, “Energy harvesting of magnetic power-line noise,” *IEEE Transactions on Magnetics*, vol. 47, no. 10, p. 4441, 2011. 59

[123] D. Vatansever, R. Hadimani, T. Shah, and E. Siores, “An investigation of energy harvesting from renewable sources with pvdf and pzt,” *Smart Materials and Structures*, vol. 20, no. 5, p. 055019, 2011. 59

[124] S. Kim, R. Vyas, J. Bito, K. Niotaki, A. Collado, A. Georgiadis, and M. M. Tentzeris, "Ambient rf energy-harvesting technologies for self-sustainable standalone wireless sensor platforms," *Proceedings of the IEEE*, vol. 102, no. 11, pp. 1649–1666, 2014. 59, 61

[125] A. Hande, T. Polk, W. Walker, and D. Bhatia, "Indoor solar energy harvesting for sensor network router nodes," *Microprocessors and Microsystems*, vol. 31, no. 6, pp. 420–432, 2007. 58

[126] C. Alippi and C. Galperti, "An adaptive system for optimal solar energy harvesting in wireless sensor network nodes," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 55, no. 6, pp. 1742–1750, 2008. 58

[127] Y. Tan, K. Hoe, and S. Panda, "Energy harvesting using piezoelectric igniter for self-powered radio frequency (rf) wireless sensors," in *Industrial Technology, 2006. ICIT 2006. IEEE International Conference on.* IEEE, 2006, pp. 1711–1716. 59, 64, 67

[128] J. A. Paradiso, "Systems for human-powered mobile computing," in *Proceedings of the 43rd annual Design Automation Conference.* ACM, 2006, pp. 645–650. 59, 67

[129] K. Vijayaraghavan and R. Rajamani, "Active control based energy harvesting for battery-less wireless traffic sensors," in *American Control Conference, 2007. ACC'07.* IEEE, 2007, pp. 3106–3111. 59, 64

[130] D. Del Testa, G. Marin, and G. Peretti, "Comparison of mac techniques for energy harvesting wireless sensor networks." 59, 60

[131] L. Mateu, C. Codrea, N. Lucas, M. Pollak, and P. Spies, "Energy harvesting for wireless communication systems using thermogenerators," in *Proc. of the XXI Conference on Design of Circuits and Integrated Systems (DCIS), Barcelona, Spain*, 2006, pp. 22–24. 60

[132] H. Bottner, J. Nurnus, A. Gavrikov, G. Kuhner, M. Jagle, C. Kunzel, D. Eberhard, G. Plescher, A. Schubert, and K.-H. Schlereth, "New thermoelectric components using microsystem technologies," *Journal of microelectromechanical systems*, vol. 13, no. 3, pp. 414–420, 2004. 60

[133] D. Ramasur and G. P. Hancke, "A wind energy harvester for low power wireless sensor networks," in *Instrumentation and Measurement Technology Conference (I2MTC), 2012 IEEE International*. IEEE, 2012, pp. 2623–2627. 60

[134] R. Sathiendran, R. R. Sekaran, B. Chandar, and B. A. G. Prasad, "Wind energy harvesting system powered wireless sensor networks for structural health monitoring," in *Circuit, Power and Computing Technologies (ICCPCT), 2014 International Conference on*. IEEE, 2014, pp. 523–526.

[135] A. Nayak, G. Prakash, and A. Rao, "Harnessing wind energy to power sensor networks for agriculture," in *Advances in Energy Conversion Technologies (ICAECT), 2014 International Conference on*. IEEE, 2014, pp. 221–226.

[136] Y. K. Tan and S. K. Panda, "Self-autonomous wireless sensor nodes with wind energy harvesting for remote sensing of wind-driven wildfire spread," *IEEE Transactions on Instrumentation and Measurement*, vol. 60, no. 4, pp. 1367–1377, 2011. 60

[137] S. Sudevalayam and P. Kulkarni, "Energy harvesting sensor nodes: Survey and implications," *IEEE Communications Surveys & Tutorials*, vol. 13, no. 3, pp. 443–461, 2011. 62

[138] T. Zou, S. Lin, Q. Feng, and Y. Chen, "Energy-efficient control with harvesting predictions for solar-powered wireless sensor networks," *Sensors*, vol. 16, no. 1, p. 53, 2016. 62

[139] V. Raghunathan, A. Kansal, J. Hsu, J. Friedman, and M. Srivastava, "Design considerations for solar energy harvesting wireless embedded systems," in *Proceedings of the 4th international symposium on Information processing in sensor networks*. IEEE Press, 2005, p. 64. 63

[140] A. Kansal and M. B. Srivastava, "An environmental energy harvesting framework for sensor networks," in *Proceedings of the 2003 international symposium on Low power electronics and design*. ACM, 2003, pp. 481–486. 63, 65

[141] A. Kansal, J. Hsu, S. Zahedi, and M. B. Srivastava, "Power management in energy harvesting sensor networks," *ACM Transactions on Embedded Computing Systems (TECS)*, vol. 6, no. 4, p. 32, 2007. 63

[142] A. Seyedi and B. Sikdar, "Energy efficient transmission strategies for body sensor networks with energy harvesting," *IEEE Transactions on Communications*, vol. 58, no. 7, pp. 2116–2126, 2010. 63

[143] D. Niyato, E. Hossain, M. M. Rashid, and V. K. Bhargava, "Wireless sensor networks with energy harvesting technologies: A game-theoretic approach to optimal energy management," *IEEE Wireless Communications*, vol. 14, no. 4, 2007. 65

[144] X. Fafoutis, T. Sørensen, and J. Madsen, "Energy harvesting-wireless sensor networks for indoors applications using ieee 802.11." in *ANT/SEIT*, 2014, pp. 991–996. 68

[145] Z. A. Eu, H.-P. Tan, and W. K. Seah, "Design and performance analysis of mac schemes for wireless sensor networks powered by ambient energy harvesting," *Ad Hoc Networks*, vol. 9, no. 3, pp. 300–323, 2011. 68, 70, 71, 74, 77, 87, 88, 89, 91

[146] C. Fujii and W. K. Seah, "Multi-tier probabilistic polling in wireless sensor networks powered by energy harvesting," in *Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP), 2011 Seventh International Conference on*. IEEE, 2011, pp. 383–388. 68, 71, 89, 91

[147] T. D. Nguyen, J. Y. Khan, and D. T. Ngo, "An adaptive mac protocol for rf energy harvesting wireless sensor networks," in *Global Communications Conference (GLOBECOM), 2016 IEEE*. IEEE, 2016, pp. 1–6. 69, 72, 88, 89, 91

[148] A. I. Al-Sulaifanie, S. Biswas, and B. Khorsheed Al-Sulaifanie, "Ah-mac: adaptive hierarchical mac protocol for low-rate wireless sensor network applications," *Journal of Sensors*, vol. 2017, 2017. 69, 73, 87, 88, 89, 91

[149] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks," in *System sciences, 2000. Proceedings of the 33rd annual Hawaii international conference on*. IEEE, 2000, pp. 10–pp. 73

[150] E. Callaway, P. Gorday, L. Hester, J. A. Gutierrez, M. Naeve, B. Heile, and V. Bahl, "Home networking with ieee 802.15. 4: a developing standard for low-rate wireless personal area networks," *IEEE Communications magazine*, vol. 40, no. 8, pp. 70–77, 2002. 73, 78, 85

[151] Z. A. Eu and H.-P. Tan, “Probabilistic polling for multi-hop energy harvesting wireless sensor networks,” in *Communications (ICC), 2012 IEEE International Conference on.* IEEE, 2012, pp. 271–275. 68, 74, 86, 87, 88, 89, 91

[152] X. Fafoutis and N. Dragoni, “Odmac: an on-demand mac protocol for energy harvesting-wireless sensor networks,” in *Proceedings of the 8th ACM Symposium on Performance evaluation of wireless ad hoc, sensor, and ubiquitous networks.* ACM, 2011, pp. 49–56. 68, 75, 77, 83, 88, 89, 91

[153] H.-I. Liu, W.-J. He, and W. K. Seah, “Leb-mac: load and energy balancing mac protocol for energy harvesting powered wireless sensor networks,” in *Parallel and Distributed Systems (ICPADS), 2014 20th IEEE International Conference on.* IEEE, 2014, pp. 584–591. 68, 76, 88, 89, 90, 91

[154] K. Nguyen, V.-H. Nguyen, D.-D. Le, Y. Ji, D. A. Duong, and S. Yamada, “Eri-mac: An energy-harvested receiver-initiated mac protocol for wireless sensor networks,” *International Journal of Distributed Sensor Networks*, vol. 10, no. 5, p. 514169, 2014. 68, 77, 78, 88, 89, 91, 92

[155] S. C. Kim, J. H. Jeon, and H. J. Park, “Qos aware energy-efficient (qaee) mac protocol for energy harvesting wireless sensor networks,” in *International Conference on Hybrid Information Technology.* Springer, 2012, pp. 41–48. 68, 72, 78, 86, 88, 89, 90, 91

[156] J. Varghese and S. V. Rao, “Energy efficient exponential decision mac for energy harvesting-wireless sensor networks,” in *Advances in Green Energy (ICAGE), 2014 International Conference on.* IEEE, 2014, pp. 239–244. 68, 79, 86, 89, 91

[157] T. N. Le, A. Pegatoquet, O. Berder, and O. Sentieys, “Energy-efficient power manager and mac protocol for multi-hop wireless sensor networks powered by periodic energy harvesting sources,” *IEEE Sensors Journal*, vol. 15, no. 12, pp. 7208–7220, 2015. 69, 80, 81, 87, 88, 90, 91

[158] O. Berder and O. Sentieys, “Powwow: Power optimized hardware/software framework for wireless motes,” in *Architecture of Computing Systems (ARCS), 2010 23rd International Conference on.* VDE, 2010, pp. 1–5. 80

[159] H.-H. Lin, M.-J. Shih, H.-Y. Wei, and R. Vannithamby, “Deepsleep: Ieee 802.11 enhancement for energy-harvesting machine-to-machine communications,” *Wireless Networks*, vol. 21, no. 2, pp. 357–370, 2015. 68, 79, 81, 83, 89, 91, 92

[160] Y. He, R. Yuan, X. Ma, and J. Li, “The ieee 802.11 power saving mechanism: An experimental study,” in *Wireless Communications and Networking Conference, 2008. WCNC 2008. IEEE.* IEEE, 2008, pp. 1362–1367. 81, 87

[161] Y. Kim, C. W. Park, and T.-J. Lee, “Mac protocol for energy-harvesting users in cognitive radio networks,” in *Proceedings of the 8th International Conference on Ubiquitous Information Management and Communication.* ACM, 2014, p. 59. 68, 69, 79, 82, 89, 91

[162] S. Sankpal and V. Bapat, “Performance evaluation of proposed sehee-mac for wireless sensor network in habitat monitoring,” *Int. J. Scientific Eng. Res*, vol. 2, no. 10, pp. 1–6, 2011. 68, 83, 86, 88, 89, 91

[163] M. Y. Naderi, P. Nintanavongsa, and K. R. Chowdhury, “Rf-mac: A medium access control protocol for re-chargeable sensor networks powered by wireless energy harvesting,” *IEEE Transactions on Wireless Communications*, vol. 13, no. 7, pp. 3926–3937, 2014. 68, 84, 85, 87, 88, 89, 91

[164] Y. He, X. Cheng, W. Peng, and G. L. Stuber, “A survey of energy harvesting communications: Models and offline optimal policies,” *IEEE Communications Magazine*, vol. 53, no. 6, pp. 79–85, 2015. 87

[165] W. K. Seah, Z. A. Eu, and H.-P. Tan, “Wireless sensor networks powered by ambient energy harvesting (wsn-heap)-survey and challenges,” in *Wireless Communication, Vehicular Technology, Information Theory and Aerospace & Electronic Systems Technology, 2009. Wireless VITAE 2009. 1st International Conference on.* Ieee, 2009, pp. 1–5. 87

[166] Z. A. Eu, W. K. Seah, and H.-P. Tan, “A study of mac schemes for wireless sensor networks powered by ambient energy harvesting,” in *Proceedings of the 4th Annual International Conference on Wireless Internet.* ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), 2008, p. 78. 87

[167] G. Piro, G. Boggia, and L. A. Grieco, "On the design of an energy-harvesting protocol stack for body area nano-networks," *Nano Communication Networks*, vol. 6, no. 2, pp. 74–84, 2015. 90

[168] N. Saxena, A. Roy, and J. Shin, "Dynamic duty cycle and adaptive contention window based qos-mac protocol for wireless multimedia sensor networks," *Computer Networks*, vol. 52, no. 13, pp. 2532–2542, 2008. 90

[169] M. Keshtgary *et al.*, "Comparative performance evaluation of mac layer protocols for underwater wireless sensor networks," *Modern Applied Science*, vol. 6, no. 3, p. 65, 2012. 90

[170] M. Hawa, K. A. Darabkh, R. Al-Zubi, and G. Al-Sukkar, "A self-learning mac protocol for energy harvesting and spectrum access in cognitive radio sensor networks," *Journal of Sensors*, vol. 2016, 2016. 90

[171] D. Evans, "The internet of things: How the next evolution of the internet is changing everything," *CISCO white paper*, vol. 1, no. 2011, pp. 1–11, 2011. 92

[172] R. Ratasuk, J. Tan, and A. Ghosh, "Coverage and capacity analysis for machine type communications in lte," in *Vehicular Technology Conference (VTC Spring), 2012 IEEE 75th.* IEEE, 2012, pp. 1–5. 92

[173] M. Magno, F. A. Aoudia, M. Gautier, O. Berder, and L. Benini, "Wulora: An energy efficient iot end-node for energy harvesting and heterogeneous communication," in *Proceedings of the Conference on Design, Automation & Test in Europe.* European Design and Automation Association, 2017, pp. 1532–1537. 97, 98

[174] P.-D. Gleonec, J. Ardouin, M. Gautier, and O. Berder, "Poster: Multi-source energy harvesting for iot nodes," in *Conference on Design and Architectures for Signal and Image Processing (DASIP)*, 2016. 98

[175] W. K. Lee, M. J. W. Schubert, B. Y. Ooi, and S. J. Q. Ho, "Multi-source energy harvesting and storage for floating wireless sensor network nodes with long range communication capability," *IEEE Transactions on Industry Applications*, vol. PP, no. 99, pp. 1–1, 2018. 98

[176] O. Georgiou and U. Raza, "Low Power Wide Area Network Analysis: Can LoRa Scale?" *IEEE Wireless Communications Letters*, pp. 1–4, 2017. 98

[177] A. J. Wixted, P. Kinnaird, H. Larijani, A. Tait, A. Ahmadinia, and N. Strachan, "Evaluation of lora and lorawan for wireless sensor networks," in *2016 IEEE SENSORS*, Oct 2016, pp. 1–3. 98, 99

[178] J. Toussaint, N. E. Rachkidy, and A. Guitton, "Performance analysis of the on-the-air activation in lorawan," in *2016 IEEE 7th Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON)*, Oct 2016, pp. 1–7. 98, 99

[179] G. Piro, M. Miozzo, G. Forte, N. Baldo, L. A. Grieco, G. Boggia, and P. Dini, "HetNets powered by renewable energy sources: Sustainable next-generation cellular networks," *IEEE Internet Computing*, vol. 17, no. 1, pp. 32–39, 2013. 99, 100, 117, 123

[180] R. Ratasuk, J. Tan, and A. Ghosh, "Coverage and capacity analysis for machine type communications in lte," in *2012 IEEE 75th Vehicular Technology Conference (VTC Spring)*, May 2012, pp. 1–5. 105

[181] A. Yahya, "Introduction to lte cellular networks," in *LTE-A Cellular Networks*. Springer, 2017, pp. 1–4. 108

[182] M. Katz and F. H. Fitzek, *WiMAX evolution: emerging technologies and applications*. John Wiley & Sons, 2009. 108

[183] G. Maral, M. Bousquet, and Z. Sun, *Satellite communications systems: systems, techniques and technology*. John Wiley & Sons, 2011. 108

[184] A. Ometov, N. Daneshfar, A. Hazmi, S. Andreev, L. F. D. Carpio, P. Amin, J. Torsner, Y. Koucheryavy, and M. Valkama, "System-level analysis of ieee 802.11 ah technology for unsaturated mtc traffic," *International Journal of Sensor Networks*, vol. 26, no. 4, pp. 269–282, 2018. 108

[185] O. Tipmongkolsilp, S. Zaghloul, and A. Jukan, "The evolution of cellular backhaul technologies: Current issues and future trends," *IEEE Communications Surveys Tutorials*, vol. 13, no. 1, pp. 97–113, First 2011. 108

[186] M. Lauridsen, P. Mogensen, and L. Noël, “Empirical LTE smartphone power model with DRX operation for system level simulations,” *IEEE Vehicular Technology Conference*, no. 1, pp. 0–5, 2013. 109

[187] J. Baliga, R. Ayre, K. Hinton, and R. Tucker, “Energy consumption in wired and wireless access networks,” *IEEE Communications Magazine*, vol. 49, no. June, pp. 70–77, 2011. 109

[188] “Satellite Earth Stations and Systems (SES); Energy efficiency of satellite broadband network(ETSI TR 103 352 V1.1.1),” European Telecommunications Standards Institute, Tech. Rep., 2016. 109

[189] R. P. Liu, G. J. Sutton, and I. B. Collings, “Power save with offset listen interval for ieee 802.11 ah smart grid communications,” in *Communications (ICC), 2013 IEEE International Conference on.* IEEE, 2013, pp. 4488–4492. 110

[190] A. Bel, T. Adame, and B. Bellalta, “An energy consumption model for ieee 802.11 ah wlans,” *Ad Hoc Networks*, 2018. 110

[191] YR Inc., “Weather Statistics for Bari (Italy) Region,” 2018, accessed: 12 April 2017. [Online]. Available: https://www.yr.no/place/Italy/Puglia/Bari/statistics.html 112, 117

[192] Institute of Energy and Transport, “Photovoltaic Geographical Information System,” 2011, accessed: 21 January 2017. [Online]. Available: http://re.jrc.ec.europa.eu/pvgis/ 113, 123

[193] S. A. Kalogirou, *Solar energy engineering: processes and systems.* Academic Press, 2013. 114

[194] Autorita Energia, “Industrial Electricity Prices in Italy,” http://www.autorita.energia.it/it/dati/eepcfr2.htm., 2017, accessed: 12 April 2017. 119

[195] “National Survey Report of PV Power Applications in Italy,” International Energy Agency Co-operative Programme on Photovoltaic Power Systems, Tech. Rep., 2016. 119

[196] Z. Wang, H. Li, D. Hu, and S. Ci, “Optimal joint transmission and harvested energy scheduling for renewable energy harvesting enabled cellular network under coordinated multi-point transmission,” *EURASIP Journal on Wireless Communications and Networking*, vol. 2015, no. 1, p. 97, 2015. 124

[197] A. F. Sherwani, J. A. Usmani, and Varun, “Life cycle assessment of solar PV based electricity generation systems: A review,” *Renewable and Sustainable Energy Reviews*, vol. 14, no. 1, pp. 540–544, 2010. 125

[198] Y. Liao, F. Deschamps, E. de Freitas Rocha Loures, and L. F. P. Ramos, “Past, present and future of industry 4.0 - a systematic literature review and research agenda proposal,” *International Journal of Production Research*, vol. 55, no. 12, pp. 3609–3629, 2017. 130

[199] F. Civerchia, S. Bocchino, C. Salvadori, E. Rossi, L. Maggiani, and M. Petracca, “Industrial internet of things monitoring solution for advanced predictive maintenance applications,” *Journal of Industrial Information Integration*, vol. 7, pp. 4 – 12, 2017. 130

[200] L. Da Xu, W. He, and S. Li, “Internet of things in industries: A survey,” *IEEE Transactions on industrial informatics*, vol. 10, no. 4, pp. 2233–2243, 2014. 130, 132, 137

[201] R. Sanchez-Iborra and M.-D. Cano, “State of the art in lp-wan solutions for industrial iot services,” *Sensors*, vol. 16, no. 5, 2016. 131, 132, 137

[202] R. S. Sinha, Y. Wei, and S.-H. Hwang, “A survey on lpwa technology: Lora and nb-iot,” *Ict Express*, vol. 3, no. 1, pp. 14–21, 2017. 133, 135

[203] G. Margelis, R. Piechocki, D. Kaleshi, and P. Thomas, “Low throughput networks for the iot: Lessons learned from industrial implementations,” in *Internet of Things (WF-IoT), 2015 IEEE 2nd World Forum on.* IEEE, 2015, pp. 181–186. 133

[204] S. Mohod and R. S. Deshmukh, “Internet of things for industrial monitoring and control applications.” 134

[205] D. Hernandez, G. Peralta, L. Manero, R. Gomez, J. Bilbao, and C. Zubia, "Energy and coverage study of lpwan schemes for industry 4.0," in *Electronics, Control, Measurement, Signals and their Application to Mechatronics (ECMSM), 2017 IEEE International Workshop of*. IEEE, 2017, pp. 1–6. 134

[206] R. B. Sørensen, D. M. Kim, J. J. Nielsen, and P. Popovski, "Analysis of latency and mac-layer performance for class a lorawan," *IEEE Wireless Communications Letters*, pp. 1–1, 2017. 135

[207] A.-A. A. Boulogeorgos, P. D. Diamantoulakis, and G. K. Karagiannidis, "Low power wide area networks (lpwans) for internet of things (iot) applications: Research challenges and future trends," *CoRR*, vol. abs/1611.07449, 2016. 135

[208] Y. Song, J. Lin, M. Tang, and S. Dong, "An internet of energy things based on wireless lpwan," *Engineering*, vol. 3, no. 4, pp. 460 – 466, 2017.

[209] C. Tunc and N. Akar, "Markov fluid queue model of an energy harvesting iot device with adaptive sensing," *Performance Evaluation*, vol. 111, pp. 1 – 16, 2017. 135

[210] N. Michelusi and M. Levorato, "Energy-based adaptive multiple access in lpwan iot systems with energy harvesting," in *Proc. of 2017 IEEE ISIT Symposium*, June 2017, pp. 1112–1116. 135

[211] L. Alliance, "Member list," [Accessed: 12 August 2018]. [Online]. Available: https://www.lora-alliance.org/The-Alliance/Member-List 137

[212] S. Inc., "Low power long range transceiver, sx1272/73 datasheet," Nov. 2015, [Revised Mar. 2017]. [Online]. Available: https://www.semtech.com/uploads/documents/sx1272.pdf 140

[213] "Impact Assessment Report (DEFRA1784)," Department for Environment, Food and Rural Affairs, Tech. Rep., March 2018. 142

[214] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, "Wireless networks with rf energy harvesting: A contemporary survey," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 2, pp. 757–789, 2015. 144, 156

[215] F. Touati, A. Galli, D. Crescini, P. Crescini, and A. B. Mnaouer, “Feasibility of air quality monitoring systems based on environmental energy harvesting,” in *Proc. of 2015 IEEE I2MTC Conference*, May 2015, pp. 266–271. 144, 156

[216] N. Y. Amponsah, M. Troldborg, B. Kington, I. Aalders, and R. L. Hough, “Greenhouse gas emissions from renewable energy sources: A review of lifecycle considerations,” *Renewable and Sustainable Energy Reviews*, vol. 39, pp. 461 – 475, 2014. 161

[217] M. Romare and L. Dahllöf, “The life cycle energy consumption and greenhouse gas emissions from lithium-ion batteries,” *Stockholm. Zugriff am*, vol. 23, p. 2017, 2017. 161