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A Comparative Study on Energy Harvesting Battery-Free LoRaWAN Sensor Networks

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ABSTRACT

Sensor networks are emerging in many applications with the availability of the spreading IoT (Internet of Things) technologies. These applications having sensor networks generally do not require big data transfers, but instead, they need to send a small amount of data from time to time. Long-range wide area network (LoRaWAN) is a very good solution for this kind of communication since LoRaWAN offers long-range transmission with deep-sleep mechanism between the transmissions. However, these networks must be reliable, and from the point of energy supply for a long period of time, they should be sustainable. Since the nature of sensor-based IoT devices is being small and placable anywhere, they are generally battery-powered. With the usage of batteries, many disadvantages including limited power, cost of replacement of the dead battery, especially in rural areas, environmental concerns, etc. arise. Therefore, energy harvesting from different sources depending on the application and location of the sensor network may eliminate these problems. In this study, firstly, we focused on how the energy is consumed by the LoRAWAN communication systems by analyzing the power consumption during the transmit phase and providing necessary formulas. Secondly, by looking at the formulas, a possible optimization is recommended on the power consumption in LoRAWAN systems in order to have longer battery life. Thirdly, we have searched and analyzed energy harvesting methods and applications used by the researchers in recent years, as well as elaborating power consumptions, in typical microcontroller-controlled sensor nodes with LoRaWAN communication ability in order to provide comparative information on energy-harvesting battery-less LoRAWAN nodes.

***Index Terms*—**Communication, computer networks, IoT, system engineering, WSN

I. INTRODUCTION

With the ever-increasing IoT applications and devices, demand for obtaining and transferring information to centralized structures is becoming more popular. Sensor networks are small, compact, and sufficient to obtain all kinds of data from the metering of sources at homes, traffic monitoring on driveways, weather conditions, and monitoring different occasions. The sensor networks can be anywhere any place generally, but the data need to be transferred to central locations over long-range distances. There are several communication techniques available for transmission such as Zigbee, WiFi, Bluetooth low energy (BLE), long-range wide area network (LoRaWAN), but from the point of low power consumption, low cost, and complexity, LoRaWAN is commonly preferred. Another important reason why LoRaWAN is the best option is that the nature of the data monitored is not continuous or need not be transferred continuously which can be managed with the sleep mode mechanism provided by LoRaWAN.

LoRa patented by Semtech Corporation [1] is a long-range low-power wireless technology platform. It operates on the unlicensed radio spectrum band. LORA Chirp-spread-spectrum modulation is shown in Fig. 1.

Long-range wide area network is a wireless communication protocol developed by LoRa Alliance to address the requirements of long-range IoT devices. The protocol and its network architecture were implemented to ensure that battery lifetime, network capacity, quality of service, and security concerns were handled. The layered structure of LoRaWAN is given in Fig. 2.

Although LoRaWAN provides low power communication, its battery lifetime is still a problem. Since the sensor networks can be located in rural areas, maintenance and replacement of the batteries bring physical difficulties and extra costs. The nature of the discontinuous transmission may degrade the lifetime of the battery resulting in frequent replacements. With the increasing

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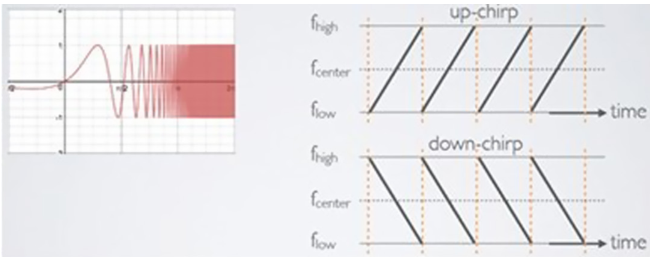

Fig. 1. Chirp-spread-spectrum (CSS) modulation.

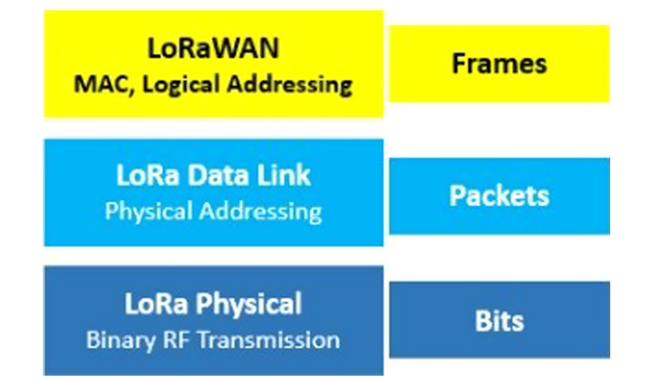

Fig. 2. LoRaWAN layered architecture. LoRaWAN, long-range wide area network.

environmental concerns, battery usage may become an issue in near future. To eliminate batteries, energy harvesting is a method studied well in the literature and in the field. Energy can be harvested from the environment such as solar irradiance, RF (Radio Frequency) waves, thermoelectric, piezoelectric, or vibration. The harvested energy from these external sources may seem not to be sufficient, but with the efficient power consumption ability of the LoRaWAN technology, this may well suit the sensor network case. Therefore, the combination of energy harvesting and LoRaWAN offers a very applicable and efficient solution for IoT-based sensor networks.

This study focuses on the researches of energy harvesting with LoRaWAN communication. The organization of this study is in the following way: we have provided an overview of end node classification for LoRaWAN nodes in section 2. This is necessary to understand and calculate the power consumption of a LoRaWAN sensor node. In section 3, power consumption and battery lifetime calculations have been provided. Since communication has a direct impact on the power consumption, the parameters of LoRaWAN communication have also been included. Though power consumption depends on various parameters, typical power consumptions

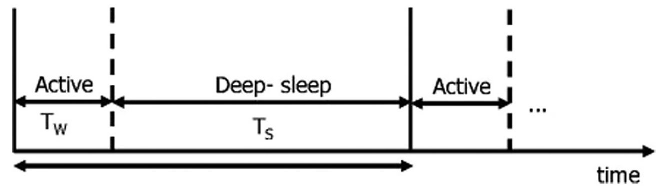

Fig. 4. Active and deep-sleep mode.

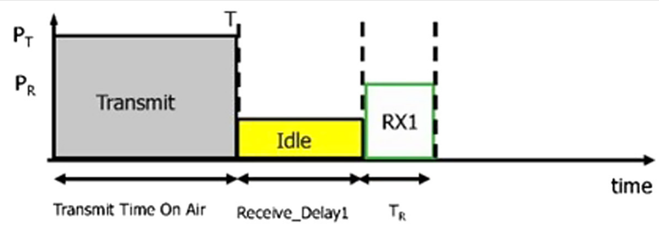

Fig. 5. Active period for class A device.

for class A type LoRaWAN node calculated by some researchers have also been given in order to give an idea. In section 4, the most recent energy harvesting methods for LoRaWAN nodes applied by researchers have been given and the achieved results have been compared. In the last section, challenges and opportunities are discussed.

II. LORAWAN END NODE CLASSIFICATION

The LoRaWAN specification defines three different classes for end nodes: class A, class B, and class C. Class A and class B use battery, while class C uses mains power. Sensor networks act as class A devices since they run on battery.

Class A, B, and C operations differ from the point of receive windows. Class A devices send their data, and during two short durations, they receive data as shown in Fig. 3.

In order to save energy, deep-sleep mode starts after two short receive windows as shown in Fig. 4.

The active period is composed of three windows such as transmission, idle, and receive windows as shown in Fig. 5. During the transmission, the device sends the data. There is an idle period between the transmit and receive windows. During the receive windows, the device expects data from Gateway.

Class B devices provide extra receive windows which are controlled by beacons sent from the gateway in addition to two short receive windows as in class A operation. This beaconed structure is shown in Fig. 6.

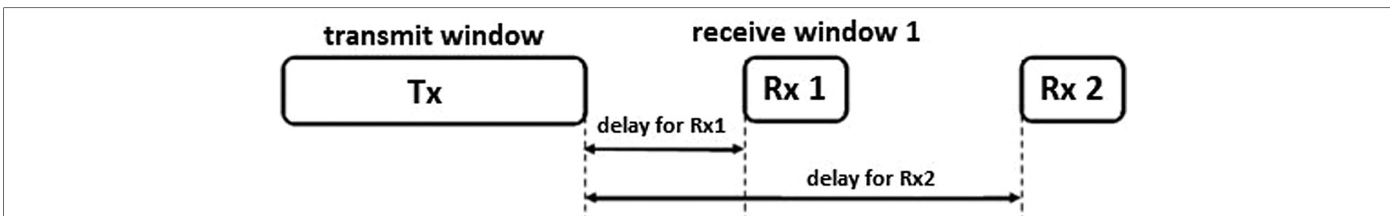

Fig. 3. Transmit and receive windows for class A device.

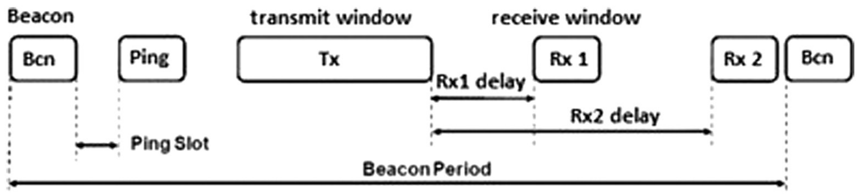

Fig. 6. Transmit and receive windows for class B device.

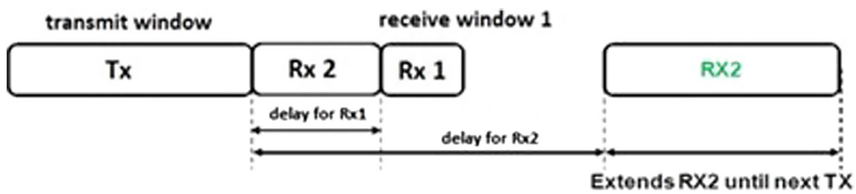

Fig. 7. Transmit and receive windows for class C device.

Class C devices provide continuous data receive windows when they have nothing to send without going to sleep mode as shown in Fig. 7. Therefore, they are not appropriate for battery-powered systems.

III. POWER CONSUMPTION CALCULATIONS AND TYPICAL POWER CONSUMPTIONS

Since LoRaWAN works in the active and deep-sleep period, Dinh et al. [2] define several parameters related to the power consumption at the sensor node in the following way:

A cycle period *T is* defined as:

$$T = T_w + T_s \tag{1}$$

where *Tw* shows active period and *Ts* shows deep-sleep period during a cycle. Since the active period is composed of transmit, idle, and receive durations, then the *Tw* is,

$$T_w = T_t + T_i + T_r \tag{2}$$

If *c(t)* is the power consumed by data transmit, receive, and idle during active period then,

$$c(t) = t\left(P_t T_t + P_i T_i + P_r T_r\right) + t P_s T_s \tag{3}$$

where P_t, P_i, P_r, and *Ps* are the powers consumed during transmit, idle, receive, and sleep durations, respectively.

If *b(t)* is the average power provided by the harvesting energy source power P_H, it can be approximately calculated as follows:

$$b(t) = P_H T_w t / T \tag{4}$$

If *E(t)* shows the residual energy at time *t,* then *E(t)* is defined such that

$$E(t) = \min\left\{E_0 + b(t) - c(t), B\right\} \tag{5}$$

where E_0 is the initial energy and *B* is the maximum capacity of the stored energy.

If $E_0 + b(t) — c(t) \leq 0$, then the system will run out of power.

Dinh et al. also define power gradient P_G as the mean of the difference between harvested power and consumed power of the node during one cycle using the above equations

$$P_G = \frac{P_H T_W - P_T T_T - P_I T_I - P_R T_R - P_S T_S}{T_T + T_I + T_R + T_S} \tag{6}$$

P_G is calculated by subtracting the consumed energy from the harvested energy per time unit during one cycle by setting the power gradient to zero, lifetime of a LoRaWAN node can be calculated as

$$L = \frac{E_0 T}{\left(P_T T_T + P_I T_I + P_R T_R\right) + P_S T_S - P_H T_W} = -P_G E_0 \tag{7}$$

Thus, the power gradient provides guidelines for parameter configuration to get the desired lifetime.

On the other hand, Delgado et al. [3] elaborate on LoRaWAN parameters that are effective on power consumption, one of which is the spreading factor (*SF*). *Spreading factor* is defined as the ratio between the chip rate and the baseband information rate. *Spreading factor* may vary between 7 and 12 and directly affects coverage.

The symbol duration *T*sym, in seconds, can be calculated using *SF* bits per symbol as

$$T_{\text{sym}} = \frac{2^{\text{SF}}}{\text{BW}} \tag{8}$$

where *BW* is the 125 kHz bandwidth. Using the LoRa frame format of the physical layer given in Fig. 8, time of air duration for the active period can be calculated. The first preamble time is calculated using

$$T_{\text{preamble}} = \left(n_{\text{preamble}} + 4.25\right) \cdot T_{\text{sym}} \tag{9}$$

where *npreamble* is the number of programmed preamble symbols, which is 8 in LoRaWAN 1.0. Then in order to find payload time on air,

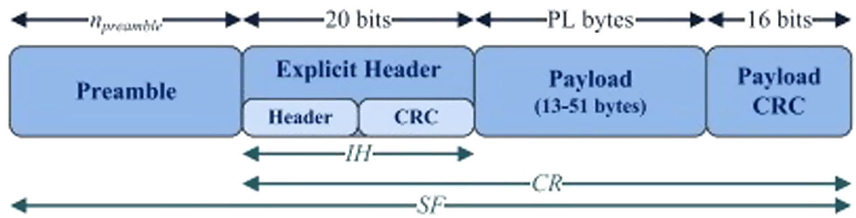

Fig. 8. LoRaWAN packet structure. LoRaWAN, long-range wide area network.

number of symbols of the payload and header are calculated using frame structure as:

$$S_{\text{payload}} = 8 + \max\left(\left\lceil \frac{8\text{PL} - 4\text{SF} + 28 + 16 - 20IH}{4(\text{SF} - 2\text{DE})} \right\rceil (\text{CR} + 4), 0\right) \quad (10)$$

where *PL* is the number of payload bytes, *CR* is the coding rate, and *IH and DE* are enable/disable header and data rate adaptation being 1/0, respectively. Now, payload time on air can be calculated using the S_{payload} as:

$$T_{\text{payload}} = S_{\text{payload}} \cdot T_{\text{sym}} \quad (11)$$

Since frame consists of preamble and payload, now the total of the air time can be calculated as the sum of these durations as:

$$T_{\text{pb}} = T_{\text{preamble}} + T_{\text{payload}} \quad (12)$$

These are also similar on air calculation during the receive time, but sensor nodes generally provide one way of communication; therefore, they are neglected from the power consumption point of view.

From these analyses, it can easily be seen that the payload transmission is directly proportional to the payload S_{payload} and symbol duration T_{sym}. The S_{payload} is mainly composed of the information that the sensor provides. Data compression techniques can be applied in order to minimize the sensor data since the information will not vary too much with time. There are several compression techniques for sensor data such as lossless, lossy, chain-based, tree-structured, and cluster-based. These techniques can save up to 60– 70% of energy. Data aggregation can also be applied by extracting minimum, maximum, and mean values of aggregated sensor data before compression increasing the overall performance. When selecting the compression algorithm, processing complexity and power has to be considered from the point of energy consumption; therefore, less complex processing algorithms must be selected since every node has already a microcontroller and this would not bring too much burden to the existing system.

On the other hand, T_{sym} is mainly dependent on the SF. The range of LoraWAN signals is also determined by the SF together with the applied power varying from 2 km up to 10 km. In order to optimize the power consumption, SF must be selected according to the distance from which the node needs to access. This can be arranged dynamically by the controller or can be fixed at the time of installation according to the distance of the nearby hop station.

Some of the works have been included here in order to provide an idea about typical power consumption in an MCU (Micro Controller Unit)-controlled LoRaWAN sensor node. Dinh et al. [2] have used WiMOD iM880Bc for simulation. They have measured power consumption of the node during transmit, receive, idle, and sleep states, that is, $P_T = 384$ mW, $P_R = 33.6$ mW, $P_i = 15$ mW, $P_S = 5.55$ mW, respectively.

Hari Bhusal et al. [4] performed an experiment using two sensors for gathering the air quality data and processing it in ATmega32u4, an 8-bit AVR-based microcontroller. Sensors data from ATmega32u4 are transferred to LoRA transceiver module, RN2483, and then it is transferred to the gateway. In Table I, the detailed power consumptions of all the components employed in the designed node are shown. It can be observed from Table I that RN2483 (LoRA WAN transceiver) consumes the most amount of power. The sleeping mode current and the power consumption of all components in the node are given in Table II. As can be observed from Table II, the real-time clock module, DS3231, consumes the most amount of sleeping power.

TABLE I. POWER CONSUMPTION OF THE COMPONENTS

Component	Current	Power
Atmega32u4	15 mA	75 mW
BME680 IAQ	15 mA	49.5 mW
BME680 Temperature	350 μA	1.2 mW
BME680 RH	450 μA	1.5 mW
BME680 Pressure	849 μA	2.8 mW
CCS811	26 mA	46.8 mW
RN2483	38.9 mA	128.37 mW
DS3231	200 μA	725 μW

TABLE II. SLEEP POWER CONSUMPTION OF THE COMPONENTS

Component	Current (μA)	Power (mW)
Atmega32u4	12	60
BME680	1	3.3
CCS811	19	62.7
RN2483	1.6	5.28
DS3231	100	363
Total	143.6	494.28

TABLE III. VOLTAGE NEEDED TO COMPLETE A TRANSMISSION CYCLE

		Payload (Bytes)				
EH (mW)	**SF**	**16**	**24**	**32**	**40**	**48**
1	**7**	2.5628	2.6105	2.6591	2.7086	2.7846
	9	3.228	-	-	-	-
	11	-	-	-	-	-
10	**7**	1.9604	1.9943	2.0289	2.0643	2.1186
	9	2.4184	2.5975	2.7919	3.0028	3.115
	11	-	-	-	-	-
100	**7**	1.8183	1.8224	1.8266	1.8309	1.8378
	9	1.8732	1.8995	1.9302	1.9661	1.9862
	11	2.4617	3.0976	-	-	-

SF, spreading factor.

TABLE IV. TYPICAL ENERGY HARVESTING POTENTIAL OF VARIOUS SOURCES

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

Carmen Delgado et al. [3] have studied power consumption under different SF and payloads. Table III shows power consumption for various payload sizes and SFs.

IV. ENERGY HARVESTING FOR BATTERY-FREE LORAWAN DEVICES USED CASES

In this section, a rich literature survey is presented that focus on different energy harvesting sources. Researchers provide sufficient information and data which make the optimum selection of the source possible according to the natural and manmade environmental conditions. Most of the researchers not only provide energy harvesting information but also design and operate a microcontroller -based LoRaWAN sensor node. From the presented works, researchers can easily calculate or estimate typical power consumption rates for such a network according to the information size and periodicity of the sensor information of their own that will be transmitted by the node.

The environmental energy sources to harvest energy offer a very wide variety of choices. Peruzzi and Pozzebon [5] have made a survey and listed them, among which radio frequency is the most commonly used since energy can be harvested independently of external conditions like weather, light, and heat; however, photovoltaic and thermoelectric are also common sources of energy. The typical energy harvesting potential of these various sources has been provided by Sherazi et al. [6] in Table IV.

There are several used cases in the literature using different energy harvesting methods, but their system architecture is generally the same. A typical energy harvesting LoRaWAN sensor end node consists of energy harvesting device, storage, microcontroller, and LoRaWAN communicator.

Dinh et al. [2] have visualized, which is shown in Fig. 9. They have developed a microcontroller-controlled sensor node connected to LoRaWAN communication unit which sends and receives data from the gateway. System harvests energy from light. Experiments showed that the system can be in transmit state for 4.82 hours, in

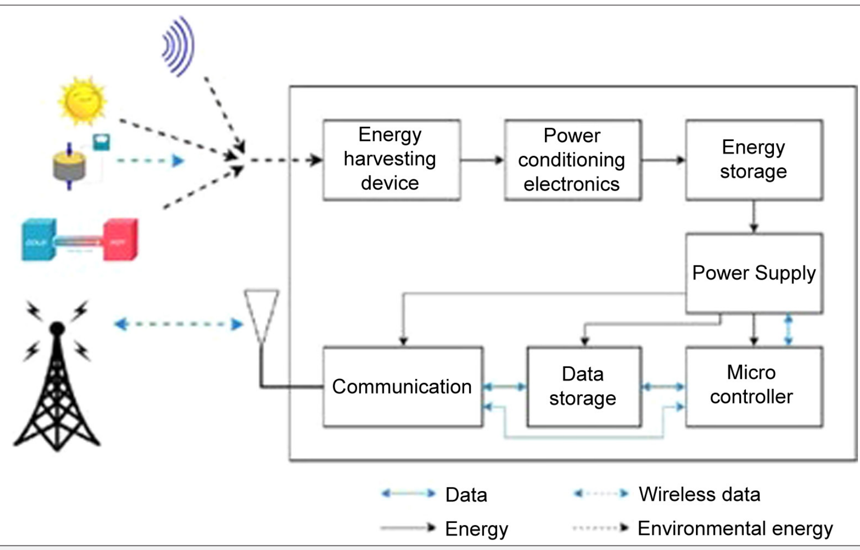

Fig. 9. A typical energy harvesting LoRaWAN sensor end node architecture. LoRaWAN, long-range wide area network.

receive state for 55 hours, and in idle state for 123.3 hours without entering sleep mode.

Hari Bhusal et al. [4] also used solar panels to harvest energy to power up MCU-controlled air quality measurement sensing carbon dioxide, amount of humidity, pressure levels, temperature, and the total organic volatile compounds and gases. The energy harvesting module included a 3.5 W-rated solar panel of size 210 mm × 113 mm × 5 mm, a charger, a storage element, and lithium-ion battery of 2000 mAh capacity. When panels fully charge 2000 mAh battery, the node lasts for 285 hours.

Kim et al. [7] selected a flexible thermoelectric generator (f-TEG) to harvest energy for wireless sensor network. They used f-TEG material around heat pipes. The size of the material used was about 140 × 113 mm^2 in area and they have harvested energy of about 272 mW from the heat pipe at a temperature of 70°C. Their LoRa coverage had a range of about 500 m.

Loubet et al. [8] have utilized a wireless power transmission system powered by an RF source driven by the same frequency band that the communication system uses. The sensor node measures temperature and relative humidity and sends data using the LoRa communicator.

Orfei et al. [9] proposed a mechanical harvester based on the vibrations of a bridge using supercapacitors. In their experiments, they tested the feasibility of LoRa communications on battery-less devices. They estimated that within every transmission, less than half of the energy stored in the supercapacitor of 100 mF is used, but even if they estimated the time required to charge the supercapacitor to its maximum voltage of 3.3 V was 3.5 hours, the number of vehicles passing along the bridge has a direct impact on these values. They showed that super capacitors are more designed for infrequent transmission.

Dalpiaz et al. [10] used electrical induction as a power source and a capacitor of 22 mF, to be used in smart grids. They have harvested energy from the same load under monitoring and estimated a few seconds of periodicity for measurements and transmissions but considering energy harvesting powers up to 1465 W, which is not feasible when considering environmental energy harvesting.

Finnegan et al [11] have investigated the boundaries of the harvested energy from RF sources such as TV transmitters, base stations, and other RF sources in different locations. Rectifying antenna is used to harvest RF energy and they have provided some figures on available RF energy and harvested electric energy. They have presented the limits of harvested energy according to the transmission cycles.

Meli et al [12] used low light energy to harvest the required energy for transmitting sensor data at every 10-minute intervals. Asenov S. and Tokmakov D. [13] have also made experimental verification on harvesting energy from a 10-V solar panel broadcasting 60 ms temperature and pressure data with a total of 87 mA power consumption. On the other hand, Bruzzi et al. [14] selected polycrystalline silicon photovoltaic cells to harvest energy from artificial light for indoor sites and to simulate an MCU-controlled sensor network waking up every 8 hours and every 1 hour to transmit the temperature data safely under 4000 K LED light.

An alternative approach to energy harvesting which is wireless power transfer has also been studied by researchers among whom is Tjukovs et al [15]. RF-DC (Radio Frequency - Direct Current) converter (rectifier) together with antenna form called the rectenna has been used in 869.5 MHz frequency and RF power levels from −20 dBm to 2 dBm. Power obtained has been varied from 0 µW to 900 µW according to the distance between the transmitter and the rectenna. 500 µW is assumed to be sufficient for regular sensor information transmissions in non-critical environment monitoring applications using LoRaWAN.

A comparison for various types of energy harvesting researches on LoRaWAN nodes is given in Table V.

V. DISCUSSION

From the given researches, it is quite apparent that with the utilization of LoRaWAN communication, energy harvesting provides

TABLE V. A COMPARISON OF VARIOUS ENERGY SOURCES FOR LORAWAN SENSOR NODE

Researchers	Energy Source	Communication	Harvested Energy	Consumed Energy	Year	Application
Dinh et al. [2]	Light	LoRaWAN	1850 mWh by 100 mW EH	438.15 mW	2021	MCU-controlled sensor node
Bhusal et al. [4]	Light	LoRaWAN	1.43 W/hour	25.9 mW/min	2020	MCU-controlled air quality measurement sensing carbon dioxide, amount of humidity, pressure levels, temperature, and the total organic volatile compounds and gases
Kim et al. [7]	Thermoelectric	LoRa	272 mW/70C	52 mW	2018	Remote monitoring of the heat pipe temperature, ambient temperature, humidity, and CO2
Loubet et al. [8]	RF	LoRaWAN	450 µW max	214 mJ	2019	WSN (Wireless Sensor Network) system to monitor the the health of the structure in the construction domain
Orfei et al. [9]	Kinetic	LoRa	330 mJ	124 mJ	2016	Monitor the road condition measuring the temperature of the road and existence of water if any.
Dalpiaz et al. [10]	Electromagnetic	LoRa	2.5 V/10 minutes	14.5 mJ	2018	MCU-controlled energy monitoring system
Tjukovs et al. [15]	WPT	LoRaWAN	400 µW/110 m	1.2 mJ	2018	Experimental wireless sensor network

self-sufficient energy for MCU-controlled sensor networks. Especially experimental verifications show us clear electrical values of harvested and consumed energy, but one should note that these values extremely depend on the environmental conditions, locations, and the materials used in the experiments.

It is obvious that harvesting energy from the monitoring source itself like electrical wires for smart grid networks or pipelines etc. eliminates power problems. In addition to these special cases, wireless power transfer can be an alternative solution as shown in the researches in case of not having sufficient RF waves. Although this concept contradicts with energy harvesting, it still offers an acceptable solution to the energy bottleneck in some cases.

However, none of the documents cited here was interested in compressing the sensor data which by nature is very suitable for compression. When literature has been searched for sensor data compression, there are good researches and different approaches such as data aggregation or estimation techniques that can save up to 70% energy.

VI. CONCLUSION

The aim of this study was to give two main understandings of power consumption and energy harvesting of a LoRaWAN system. Power consumption of a LoRaWAN transmitter has been analyzed providing all necessary formulas and deriving main parameters from these formulas in order to optimize power consumption. Two important parameters are emphasized as SF and payload which are mainly composed of the information that the sensor provides. An optimization of these two parameters can provide less power consumption enabling longer availability for a battery-less LoRaWAN sensor node. In the second part of the survey, literature has been searched for different energy sources which are used for energy harvesting. The survey may seem to be not too much, but two concerns have been taken while selecting papers. Firstly, papers with solid results have been selected to provide sufficient information to make right decisions on energy sources to be used, and secondly, researches that use different sources have been selected so that the new researchers will have the chance to compare the results with their own if they use the same energy source.

While payload and SF have been specially emphasized in this study as not studied by the cited researches, some other parameters are also found to be effective in power consumption. They are:

- The communication parameters of LoRaWAN, BER, bandwidth, CR;
- Selection of microcontroller that has lower power consumptions;
- Designing power conditioning system according to the selected harvesting method.

Further analysis can be performed on these parameters for the new researches.

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