Evaluation of Energy Consumption of LPWAN Technologies

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Evaluation of Energy Consumption of LPWAN Technologies

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Abstract The modern technological innovations provide small radios with ability to broadcast over vast areas with minimum energy consumption that will significantly influence the future of the Internet of Things (IoT) communications. The majority of IoT implementations demand sensor nodes run reliably for an extended time. Furthermore, the radio settings can endure a high data rate transmission while optimizing the energy-efficiency. The LoRa/LoRaWAN is one of the primary Low-Power Wide Area Network (LPWAN) technology that has highly enticed much concentration recently from the community. The energy limits is a significant issue in wireless sensor networks since battery lifetime that supplies sensor nodes have a restricted amount of energy and neither expendable nor rechargeable in most cases. A common hypothesis in previous work is that the energy consumed by sensors in sleep mode is negligible. With this hypothesis, the usual approach is to consider subsets of nodes that reach all the iterative targets. These subsets also called coverage sets, are then put in the active mode, considering the others are in the low-power or sleep mode. In this paper, we address this question by proposing an energy consumption model based on LoRa and LoRaWAN, that model optimizes the energy consumption of the sensor node for different tasks for a period of time. The proposed analytical approach permits considering the consumed power of every sensor node element; furthermore, it can be used to analyse different LoRaWAN modes to determine the most desirable sensor node design to reach its energy autonomy.

Keywords Internet of Things (IoT) · LPWAN · LoRa · LoRaWAN · Energy Consumption · Performance Evaluation

1 Introduction

The term Internet of Things(IoT), being an umbrella indication, covers a wide area of applications. The Internet of Things (IoT) employing wireless communications in the industrial field is growing extremely mainstream. The conversion from conventional wired infrastructure to wireless connection has facilitated further devices, applications, and services to interact with each other. IoT assures the integration of smart objects, sensors, internet protocols, and wireless technologies, etc, to distribute date and interact between themselves through specified protocols [1]. The IoT is prepared to eliminate the restriction of the internet merely to computers and smartphones. Moreover, to increase it to a variety of other aspects of our environment, i.e., home automation, digitized health, smart parking, smart farming, smart grids, industrial internet, process controlling, etc [2]. That opens up an enormous amount of possibilities, that serve multiple industries as well as enhance the well-being of individuals. IoT's key

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characteristics involve smart objects' capability to collect data comprehensively, send the required data in a secure mechanism, and create intelligent post-processing on the accumulated data [3]. The fast-growing among electronics, RF-technologies, networking, and the development in computational power have made internet empowering technologies more affordable, and continue to do so. The employment of Radio-frequency identification (RFID), Quick Response (QR) codes, and wireless technology are determined by their short-range and high-throughput. Furthermore, the cellular networks 2G, 3G and 4G that are long-ranged and have a high throughput are forming approaches to facilitate the interaction between humans, people to devices, and devices to devices [4]. Machine-type communications (MTC) is a model that empowers devices to transfer information autonomously and execute transactions without human interference. MTC technologies can connect devices to virtually everything within a single network. These devices merge in a smart grid, business, energy sector, and smart houses [5,6]. SSensor nodes enable the IoT paradigm by the transformation of wireless connectivity in a natural and harsh environment. Thus, nodes that need function among various technologies should feature large-scale network infrastructure with low power consumption. These restrictions promote to introduce the Low Power Wide Area Network (LPWAN). The LPWAN technologies presented in Figure 1 shown a radical communication that assures the long-range with low power consumption and low-cost deployment [7]. It is mainly intended for such applications that expect few messages per day to be transmitted in a wide radio range. In that regards, SigFox, LoRaWAN, and NB-IoT are the most popular technologies [8]. Energy consumption represents an essential role in IoT, particularly for battery-powered devices, which are installed in remote or unattainable areas where a lifetime of 10+ years is coveted. Each task of the consumed power needs to be carefully developed, and the design choices have a significant influence on the product lifetime. These design choices and trade-offs will be the subjects for investigation in this paper.

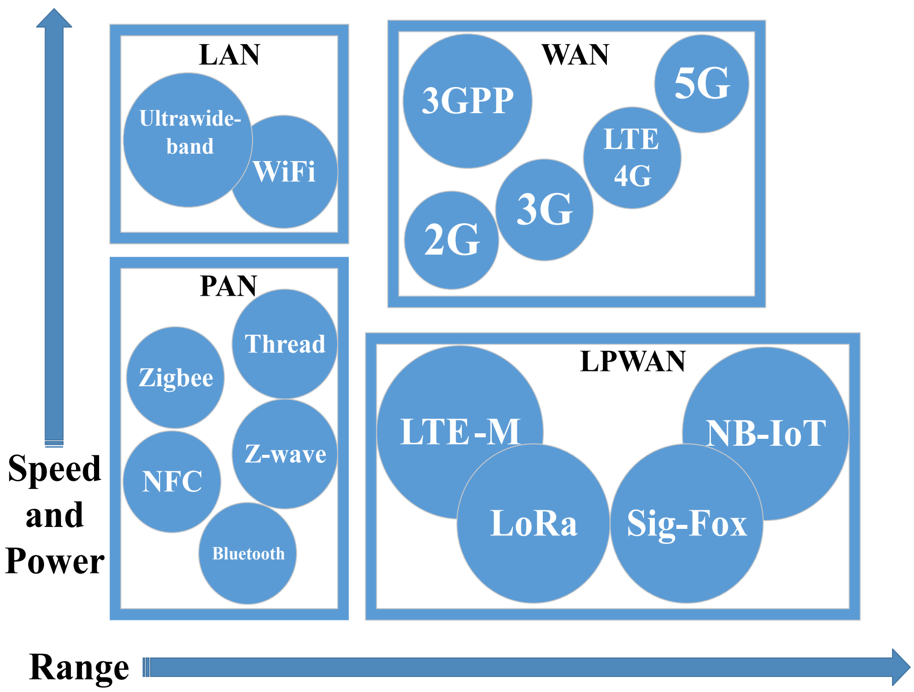

Fig. 1: Low Power Wide Area Technologies

The proposed energy consumption model for sensor nodes using LoRa modulation and LoRaWAN protocol. This model is estimated utilising distinct LoRaWAN modes. The main purpose of this research work focuses on the energy efficiency of the LoRaWAN network that examines massive of concomitantly transmitting end-devices uniformly distributed around the gateway in a range of many kilometres. We investigate different scenarios, wherein one case a sensor node transmits data to gateways except considering outage probability caused by the imperfect channel behaviour. Furthermore, we investigated the re-transmission of message certain times over the uplink radio channel and required an acknowledgement from the gateway in one of two receive windows. Additionally, the purpose of this research is to develop a model and identify the properties that are related to LPWAN technologies' power consumption, that enables the developers to determine device lifetime and estimate the required battery energy capacities for systems. Moreover, the goal is to define the influence use cases have on the consumption. The paper proceeds as follows. Section 2 presents related works. The background and the key characteristics of LoRa and LoRaWAN present in section 3. Section 4 defined the problem statement. Investigates our proposed energy consumption mathematical analysis in Section 5, followed by the simulation and numerical results are explained in Section 6. Finally, conclusion and future works are presented in Section 7.

2 Related Work

LPWAN, LoRa, and LoRaWAN technologies overviews are provided in [9,10]. In regards to the existing LPWAN technologies, LoRa has mainly attracted a wide variety of work because of the availability of commercial off-the-shelf radio transceiver and platforms [11,12,13]. Generally, LoRa operates with a bandwidth of 125 kHz; however, it also provides connections for bandwidths of 250 kHz and 500 kHz. The broader bands increase the resistance to fading, Doppler effects, channel noise, and long-term relative frequency for WAN devices [14]. The most recent research based on LoRa and LoRaWAN has focused on characteristics such as delay, range, throughput and network capacity [15,16]. Since the massive deployment of LoRa modulation for sensor applications, many papers investigated this new technology concerning its energy consumption. Certain studies have considered the ability of LoRa technology determining the performance for various parameter settings in indoor [17,18] or outdoor [9,19,20] configurations. Bor and Roedig introduce an algorithm for obtaining the most reliable transmission setting for a particular transmission channel in [15]. It operates a type of binary search of the parameter space, testing each setting for its packet response rate till a proper setup is found. The intention is to balance the cost of suitable finding parameters versus the packet delivery rate achieved. Cattani analysed the optimal parameter settings in [21] by measuring the packet reception rate and energy efficiency for three types of the channel (underground, indoor, and outdoor) considering several LoRa parameter settings. The authors considered the effect of environmental parameters on channel performance and observed that high temperature at the node decreased the packet delivery rate considerably. The analytical model of LoRa energy consumption assigned to sleep, transmit and receive conditions are proposed [22,23]. The authors in [22] presented an optimization of the downlink communication in LoRaWAN while considering only a single SF, by deploying a battery lifetime up to 1 year is achieved with 0.44 mJ energy consumption. On the other hand, the authors in [23] present an accurate calculation for message transmission time in LoRa. However, their study does not provide focus on the MAC layer mechanism, especially message acknowledgement, receive windows (RX1 and RX2), and re-transmissions. A short-range RF module CC1100 is used and presented in [24], which does not have the capabilities of LoRa technology. Furthermore, The authors explained the modelling of a sensor node aimed to wireless sensor network applications. A detailed explanation and illustration of LoRaWAN classes and their corresponding power consumption are discussed in [25]. A single gateway uplink model determining the path loss attenuation and Rayleigh fading are proposed in [26]. The authors utilized a stochastic geometry to model network interference and then disconnection and collision probabilities. Another energy estimation model is presented in [27]; the main object of this study is to obtain a low power consumption of sensor nodes. To conserve power, the authors have assumed that the communication module and the micro-controller must be in the idle state as much time when they are not active. This research introduces exciting findings; nevertheless, LoRa and LoRaWAN technologies are not investigated in this study. Recently numerous investigation illustrated the power usage and current level of wireless sensor nodes in LoRaWAN networks without proposing an energy model to determine and enhancing energy consumption and battery lifetime [28,29,30]. The authors in [31] proposed an energy consumption model for LoRaWAN devices. They determine the energy consumption for different devices, regardless of the network behaviour. Determination data are obtained employing the existing common LoRa hardware platform, MultiConnect mDot, based on the SX1272 transceiver. In contrast with [31], our proposed work estimates the energy cost and also evaluates the energy efficiency of LoRaWAN networks, considering the network with massive number of end nodes. The main goal of this research is to gain insight into competing LPWAN technologies, especially with regards to power consumption, which can assist IoT developers make well-informed decisions when choosing internet enabling technologies. In our paper, we have examined the performance of uplink communication and modelled different scenario of the connected sensor. Moreover, we have demonstrated our energy model with optimization of LoRaWAN parameters for instance the spreading factor SF, the coding rate CR, the bandwidth BW, the payload size and the communication range. Optimizing these parameters is essential to decrease the energy consumption of the sensor node. The average power consumption of a sensor node in different transmission modes serves in identifying the operating lifetime. This research work contributes to measure the energy cost of massive uniformly distributed end-devices in LoRaWAN. The energy model takes into consideration the transmission acknowledgement and its energy consumption cost, employing various LoRaWAN scenarios.

3 LoRa and LoRaWAN Overview

This section will give an in-depth description of LoRa/LoRaWAN, covering their essential characteristics and packet structures, defining the procedure and critical parameters in transmitting information based on LoRa technology. LoRa, short for Long-Range, is a wireless communication modulation method, which employs a variety of Chirp Spreading Spectrum (CSS) to transmit information. The goal of this technology is to enhance the lifetime of battery-powered sensors with minimal cost. Long Range Wide Area Network, LoRaWAN, is the protocol, which is employed commonly with LoRa. The physical layer of LoRa is a closed and proprietary technology that maintained by Semtech, while LoRaWAN is an open standard. The LoRaWAN protocol is developed by LoRa Alliance, which involves more than 500 member companies [32]. The network architecture is a star of stars type network as shown in Figure 2.

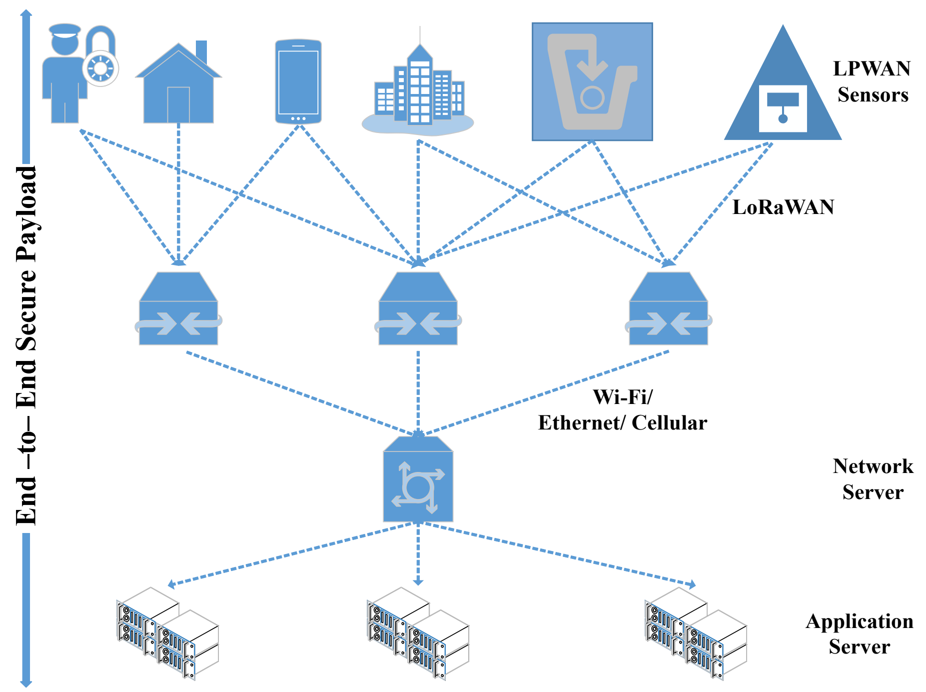

Fig. 2: LoRa Network Architecture

LoRaWAN defines three categories of devices (Class A, B, and C) concerning the application usage, which results in having different power consumption profiles for each class. Figure 3 illustrates the distinctive classes and defined as follow:

1. **Class A**: is expected to be the most commonly used class because it has the best power-saving capabilities [33]. End-devices utilize the ALOHA protocol for scheduling uplink transmission in bi-directional communication. The end-device sends a message at a random instance of time, and the gateway replies after two predefined delays. The messages in both receive windows are identical, which can cause the collision probability. Every node considers the acknowledgement in receive windows (RX1 and RX2) through downlink transmission. Time offset and data rate are the fundamental parameters of receiving windows. Failure of acknowledgement in RX1 is the only reason for enabling the RX2. The default values of RX1 Delay are 1s and 2s for RX2 Delay.

2. **Class B**: allows devices periodic receive slots and opens extra receiving slots at the scheduled times. It enables the device to receive like class A devices, furthermore a ping slot generated by the gateway to combine end-devices to receive additional windows. Therefore, a periodic beacon from the gateway for synchronization is required. The network server (NS) is informed of the listening status of end-devices. The power consumption of Class B is higher than Class A [34,35].

3. **Class C**: devices always listen to the gateway, and it implements a traditional bi-directional communication system. End nodes consume the most energy since it is the representative's the response of continuous listening of channel except while the transmission period [36].

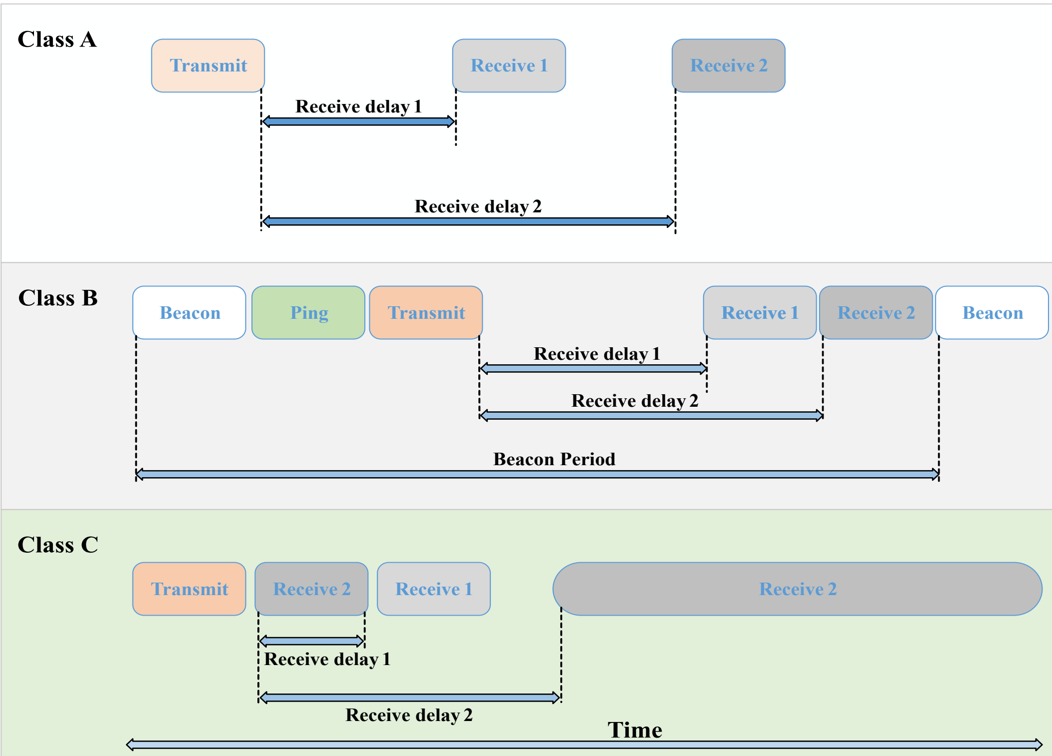

Fig. 3: Device classes in LoRa

The endless variation of frequency over time to encode data drives CSS modulation resistant versus the Doppler effect. However, the frequency offset connecting the transmitter and receiver reaches 20% of the total bandwidth without affecting the decoding performance. Accordingly, crystal installed in a transmitter does not expect to have maximum efficiency, which decreases the manufacturing cost of the LoRa transmitter. There are the following several fundamental configuration parameters of LoRa radio:

- **Spreading Factor(SF)**: is defined as the number of chirps per symbol. Also, it is a critical variable in LoRa, which has a significant influence on both the range, transmission speed and power consumption. LoRa has six different values in the range 7 to 12 to control the data rate of the transmitted signals [37]. Higher SFs provide more extensive coverage areas; however, as a drawback, they increase the time-on-air (ToA) of LoRa packets and therefore the power consumption as well. The signals sent using different SFs are mutually orthogonal (quasi) , meaning that messages can be transmitted concurrently without causing a collision. The symbol period, Ts, is given by:

$$T_s = \frac{2^{SF}}{BW} \tag{1}$$

  So, the symbol rate, Rs, is the reciprocal of the symbol period:

$$R_s = \frac{BW}{2^{SF}} \tag{2}$$

  The chip rate, R_c, which is the number of pulses per second, can be calculated as:

$$R_c = R_s \times 2^{SF} = \frac{BW}{2^{SF}} \times 2^{SF} = BW \tag{3}$$

  The modulation rate or bit rate, R_b, is:

$$R_b = SF \times \frac{BW}{2^{SF}} \tag{4}$$

- **Carrier Frequency (CF)**: Carrier Frequency (CF): It is the frequency employed to broadcast the information from node to gateway. LoRa operates at unlicensed frequency ISM bands in Europe and the U.S. at 865-870 MHz and 915 MHz, respectively [38,39].
- **Bandwidth (BW)**: There are three bandwidth options for LoRa communication, i.e., 125 kHz, 250 kHz, and 500 kHz. In Europe, the 125 kHz is usually used for the 863-870 MHz frequency band. For the fast transmission, it is more beneficial to use 500 kHz bandwidth, and if an extended coverage area is required, 125 kHz is recommended. Table 1 reviews the relationship between BW, SF, and Receiver Sensitivity. An increase in bandwidth will lower the decoder sensitivity, moreover, the spreading factor has a proportional relationship with receiver sensitivity.

Table 1: Semtech SX1276, Sensitivity of LoRa Receiver (dBm) [9]

BW	SF7	SF8	SF9	SF10	SF11	SF12
125 kHz	-126.50	-127.25	-131.25	-132.75	-134.50	-133.25
250 kHz	-124.25	-126.75	-128.25	-130.25	-132.75	-132.25
500 kHz	-120.75	-124.00	-127.50	-128.75	-128.75	-133.25

- **Coding Rate (CR)**: Coding rate expression is $CR = \frac{4}{4+n}$ where $n \in$ [1,2,3,4]. Minimizing the value of the code rate provides higher time-on-air (ToA) to transfer information. LoRa uses forward error correction. Whereas LoRa modulation is proprietary, reverse engineering endeavours determine that LoRa employs Hamming codes [40, 41], that increases the overhead to the transmitted messages and the nominal bit rate as the following:

$$R_b = SF \times \frac{BW}{2^{SF}} \times CR \quad (5)$$

The Hamming codes attach error detection and correction capabilities to the code. By rising n by one, the code distance increases by one, which presents the capabilities specified in Table 2 [42]. The reduction in code rate leads to a decrease in the Packet Error Rate (PER) as opposed to the interference. For instance, an information message sent with a 4/8 code rate is more elastic against channel implications as compared to a code rate of 4/5. As shown in Table 2 that the least coding rate compares to a parity check bit, that can detect all uneven number of bit failures. The maximum that can be detected is 3-bit errors and it can correct 1 bit error.

Table 2: Achievable error detection and correction capabilities in LoRa

Code Rate	Error Detection [Bits]	Error Correction [Bits]
4/5	Parity	0
4/6	1	0
4/7	2	1
4/8	3	1

Transmission: The LoRa sent messages including a preamble and payload:

$$T_{packet} = t_{preamble} + t_{payload} \quad (6)$$

The payload size can be varied by enabling or disabling portions of the payload together with adjusting the spreading factor, coding rate and significant payload size. The number of payload symbols can be modelled as [43]:

$$N_{Pload} = 8 + max\left(ceil\left(\frac{[8PL - 4SF + 28 + 16CRC - 20H]}{4\,(SF - 2DE)}\right)(CR + 4)\,, 0\right) \quad (7)$$

where :

- PL : Number of Payload bytes.
- SF : Spreading Factor $7 - 12$.
- H : Header : 0 = enabled, 1 = no header.
- DE : Low Data Rate Optimization: 1 = enabled , 0 = disabled.
- CR : Coding rate.
- CRC: Cyclic Redundancy Check.

PL is the payload including both settings and the message payload as:

$$PL = PL_{settings} + PL_{useful} \quad (8)$$

The number of preamble symbols can be modelled as:

$$n_{preamble} = 4.25 + n_{regional} \tag{9}$$

Where $n_{regional}$ is a regional constant, which is 8 in Europe.

By using the symbol duration the packet time on air can finally be represented as:

$$t_{packet} = (n_{preamble} + n_{payload}) \times t_{symbol} \tag{10}$$

Finally, multiplying the packet duration t_{packet} with the transmission power consumption P_{TX}, the energy consumption per transmission E_{packet} can be determined as shown below:

$$E_{packet} = t_{packet} \times P_{TX} \tag{11}$$

Duty Cycle: European frequency bands are 867-869 MHz its duty cycle is 1%. It takes the time consumption t_{packet} for a node to send a group of data using this frequency band, so the current sending cycle of this node is T_C. The node can send data again after the end of the cycle, that can be determined as $T_C - T_{TC}$. So, the number of data transfers per day N_{msg} can be written as the following:

$$N_{msg} = \frac{24}{T_C - t_{packet}} \tag{12}$$

4 Problem Statements

LPWAN technologies must cope with the massive number of end nodes transmitting low data volume. Several methods are considered recently, which helps in the resolution of energy consumption and scalability problems. The design preferences, as mentioned in the background Section 3, heavily influence device battery lifetimes. Designing a low power consumption device within IoT requires multidisciplinary abilities within hardware, software and RF. Also, the use cases need to be taken into concern, when designing devices, as they are rigidly connected to the consumption. That drives to the questions which our paper aims to answer:

- How can LPWAN devices' power consumption be minimized?
- How do different use cases affect the power consumption of LPWAN devices?

5 Methods/Experimental

Considering the linear behaviour of a battery in ideal scenarios. However, in a real-life scenario, battery characteristics degrade over time. Hence, these findings will only provide the approximation on the real node lifetime. Practically, there are three significant application places where battery-less devices will benefit: (i) Inaccessible or embedded devices, (ii) Enormous expansion of IoT networks (iii) Neglect the devices after long-lifetime deployment. To demonstrate the application of our energy model, the assumed use case relevant for fine-grained environmental monitoring. For instance: monitoring the air quality, occupancy in buildings or cities, or for tracking goods in immense logistics warehouses.

5.1 Sensor Node Design

The sensor node is usually a micro embedded system; its processing capacity, storage capacity and communication capacity are limited. For better performance, the nodes need closer cooperation of hardware and software system. The proposed node model is shown in Figure 4, and the sensor nodes can use the access point of the LoRa/LoRaWAN radio module. The three main units of the sensor are perception unit, processing unit and a communication unit.

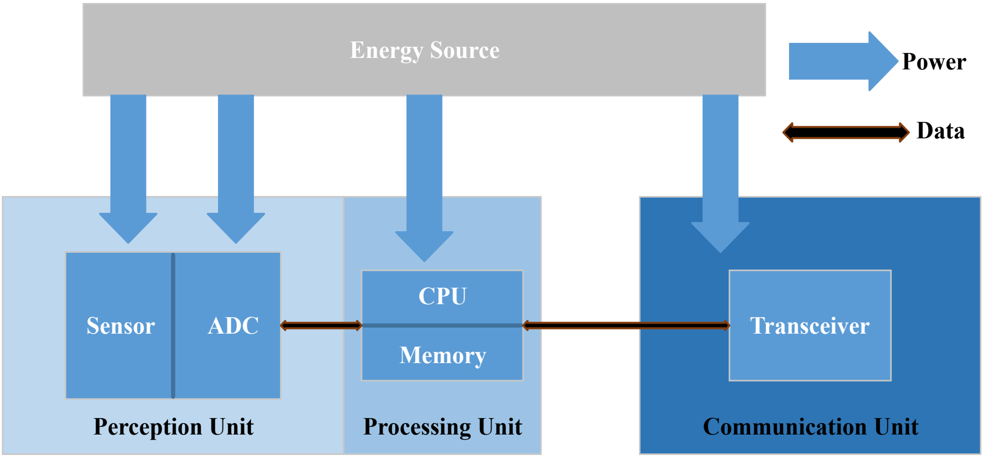

Fig. 4: Senor node

- **Perception unit:** is composed of a sensor unit and an Analog to Digital Converter (ADC). The sensing unit is mainly used to collect all kinds of information in the real world, such as temperature, humidity, pressure, sound and other physical details. Afterword, convert the analogue information collected by the sensor into digital data, which is handed to the processing unit for processing.

- **Processing unit:** is composed of central processing unit (CPU) and the memory. The processing unit is responsible for the data processing and operation of the whole sensor node, storing the collected data of this node and the data sent by other nodes. Our study in this paper uses embedded system that is based on the STM32L073 microcontroller from ST Microelectronics [1] because these microcontrollers can be optimized for very low power consumption.

- **Communication unit:** is responsible for wireless communication with other sensor nodes, exchanging control messages and receiving and receiving data. Our model based on LoRa/LoRaWAN Semtech Sx1272 transceiver. The current usage in each state and supply voltage is taken from the datasheet of the SX1272 in [43].

5.2 Energy Model

The energy consumption of IoT sensor nodes can be illustrated by classifying the phases that the product operates in and after that the power consumed in each stage, as proposed in several publications on sensor networks [44,45]. The model implies a constant duration and consumption. When the energy consumption in one message procedure is classified, the dissemination of power dissipation relying on the phases can be defined as well as the product battery lifetime. Figure 5 shows a division to multiple phases of operation of a typical IoT sensor node. The total consumed energy E_{TOTAL} used by the two main periods is given by the equation:

$$E_{TOTAL} = E_{Active} + E_{Sleep} \tag{13}$$

Where E_{Active} is the energy consumed when the system is active and E_{Sleep} energy consumed when the system is in sleep mode.

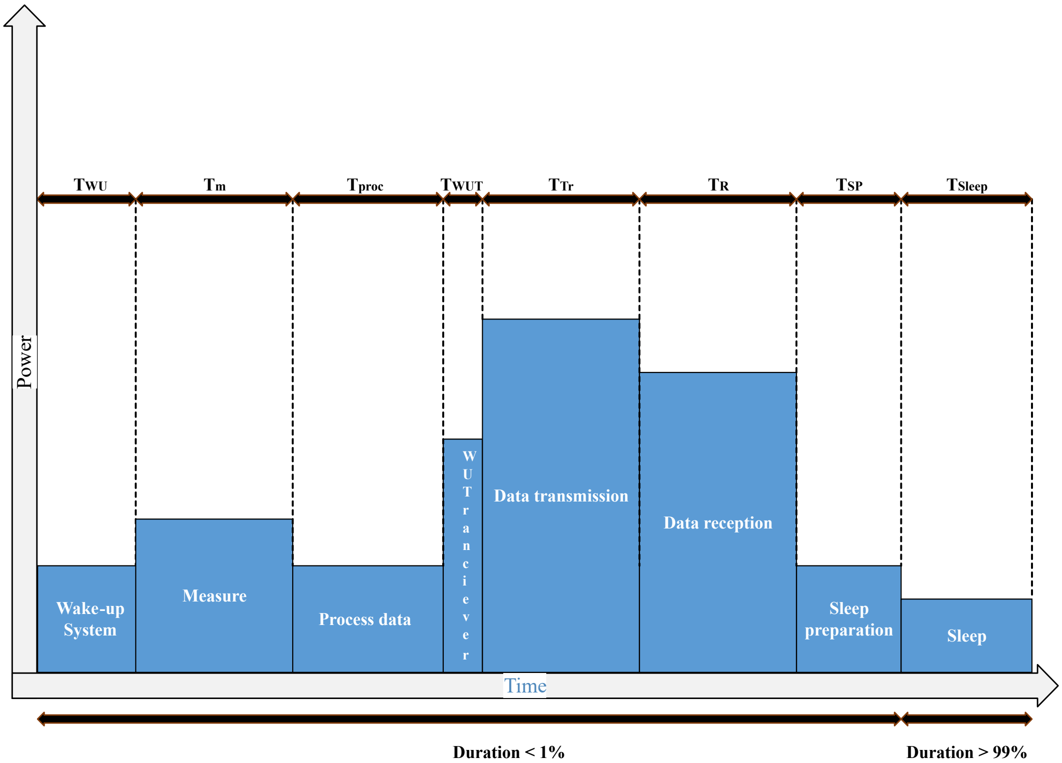

Fig. 5: General state-based energy consumption model

Our energy consumption model concerning the following assumptions:

- As considered in [48, 49] , the processing unit is in on-state along the working sequence. The presumption can enhance optimizing the MCU unit by constructing it in low-power modes through most of the activity cycle.
- A constant time duration characterizes each step of the sensor working sequence.
- The radio module sends a packet of data at a specified transmission power level.

The energy consumed in sleep mode is calculated as:

$$E_{Sleep} = P_{Sleep} \times t_{Sleep} \quad (14)$$

Where P_{Sleep} and t_{Sleep} are the power consumption and duration in sleep mode, respectively.

The energy consumed in active mode can be determined as:

$$E_{Active} = E_{WU} + E_m + E_{proc} + E_{WUT} + E_{Tx} + E_{Rx} + E_{SP} \quad (15)$$

Where the energies from the states in Figure 5 are described. The energies are determined the same way the energy in sleep mode by multiplying their power consumption with their duration as follows:

$$E_{proc} = I_{proc} \times V \times t_{proc} \quad (16)$$

$$E_{TRx} = E_{Tx} + E_{Rx} = I_{TRx} \times V \times t_{TRx} \quad (17)$$

5.3 **Lifetime Estimation**

Presented with the transaction period and consumption of the node devices [48], the output lifetime can be estimated. To determine the lifetime LT of the devices, the battery capacity E_{Bat} can be divided by the energy consumption per day E_{day} as follows:

$$LT = \frac{E_{Bat}}{E_{day}} \quad (18)$$

The energy consumption essentially relies on the number of transactions n_{msg}, which define the number of times the system is in an active state. The daily energy consumption can be determined as:

$$E_{day} = n_{msg} \times (E_{Active} + E_{Sleep}) \quad (19)$$

$$n_{msg} = n_{TX} + n_{RX} \quad (20)$$

Considering that each transaction is bidirectional shown in equation 20. Though, this is usually not the case in LPWANs as they often have more uplinks than downlinks. Taking into account, the energy consumption per day E_{day} is given by:

$$E_{day} = n_{TX} \times E_{Active} - (n_{TX} - n_{RX}) \times E_{TX} + E_{Sleep} \quad (21)$$

Where the energy from receptions is removed, if there are more transmissions than receptions.

To determine the estimated battery life by dividing the capacity rate by daily consumption. The battery capacity $C_{Battery}$ expressed in mAH as follows:

$$C_{Battery} = U \times I \times t = P_{Battery} \times t \quad (22)$$

Using equations (19), (20) and (21), we consider the battery life as D_{BL} can be expressed as:

$$D_{BL} = \frac{C_{Battery}}{E_{day}} \quad (23)$$

Furthermore,energy harvesting solution is provided in [49] deploying an analytical model of the system using a Markov Chain, moreover, the authors presented the design of the device depending on the application specification and environmental conditions (energy harvesting rate).

6 Analysis the Proposed Scenarios

In this section, we will estimate and simulate the performance of our energy consumption model using Class-A dense LoRaWAN network consisting of a single gateway and various end nodes. The presented range is sufficient for our application, and this enables for saving the use of the battery. The uplink transmission of the end nodes is based on the ALOHA protocol. Furthermore, scenarios are proposed for the sensor node battery usage acceleration and transmit therefore the modules send data are every 30 s.

This leaves the device with three possible message transaction scenarios illustrated in Figure 6 as follows:

- **Scenario 1:** An unacknowledged transmission, where both receive windows are ignored.
- **Scenario 2:** An acknowledged transmission, where only one receive window is decoded Rx2.
- **Scenario 3:** An acknowledged transmission, where only one receive window is decoded Rx1.

The sensor node implements acceleration measurement and sends the acceleration value every 30 s. The operating frequency considered for the microcontroller is equal to 4 MHz. Table 3 illustrates the power and time parameters of the model. These parameters are given in the datasheets of BMA220, STM32L073 and SX1272 [43, 46, 47].

Table 3: Characteristics of sensor node tasks [48]

Task	Time Duration(ms)	Consumed Power(mW)
Sensor (BMA220)	25	10.5
Data transmission (SX1272)	6.5	92.4
MCU STM32L073 (4 MHz)	33.5	1.8

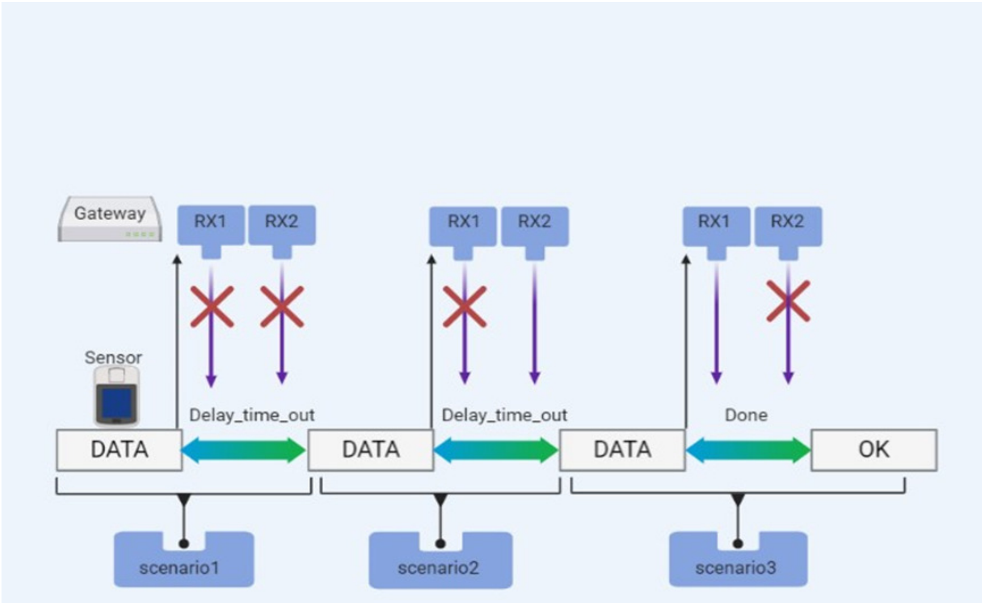

Fig. 6: Sensor scenarios

6.1 Consumed Energy: Scenario 1

In this scenario, we suppose that the sensor node has not received RX1 and RX2. The main energy consumers are the micro-controller unit, the sensor unit and the transceiver unit. Suppose the down-link message is lost for any reason. The LoRa specification recommends sending packets up to 8 times. Figure 7 presents the energy consumption amount of the principal communicating sensor. As shown before, the major energy consumers are the microcontroller unit (EMCU = 0.1 mJ), the sensor unit (Em = 0.29 mJ) and the LoRa Data transmission (ETr = 0.59 mJ). The sensor node lifetime illustrates in Figure 8 is using the battery characteristics with capacity equals 50 mAh, and the supply voltage of 3 V. The sensor node autonomy is about 201 days when the measurement period is equal to 30 s.

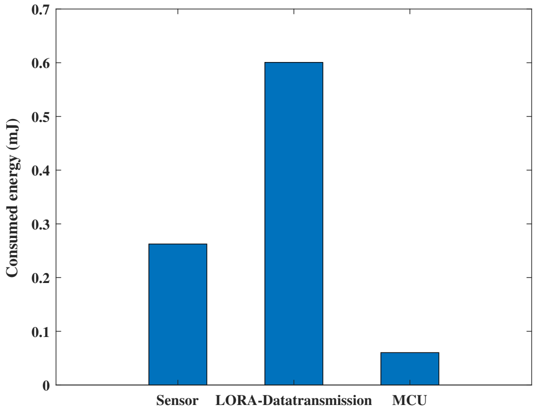

Fig. 7: Energy consumption of sensor node: Scenario 1

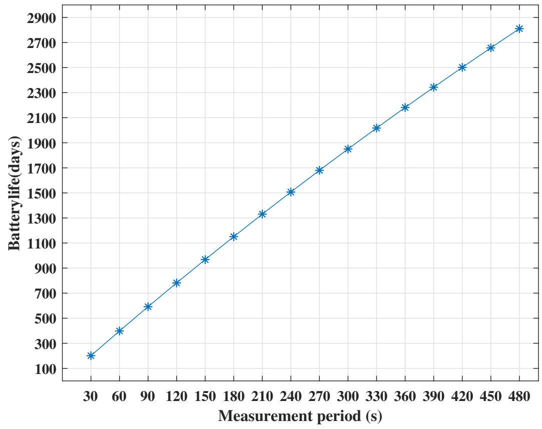

Fig. 8: Sensor node lifetime: Scenario 1

6.2 **Consumed Energy: Scenario 2**

In this scenario, we consider that the sensor node transfers data to the gateway then receives an acknowledgement RX2 without receiving the RX1 response to verify that the transmission was successful. The energy consumption by the communicating sensor illustrates in Figure 9 . As shown, the distinction from Scenario 1 is the dissipated energy by the LoRa receiver Rx2 (ER = 0.42 mJ) and the consumed energy by the MCU unit. Figure 10 presents the sensor node lifetime using the battery characteristics (capacity equals 50 mAh and supply voltage of 3 V). The sensor node autonomy is about at 139 days when the measurement period is equal to 30 seconds shorter than Scenario 1.

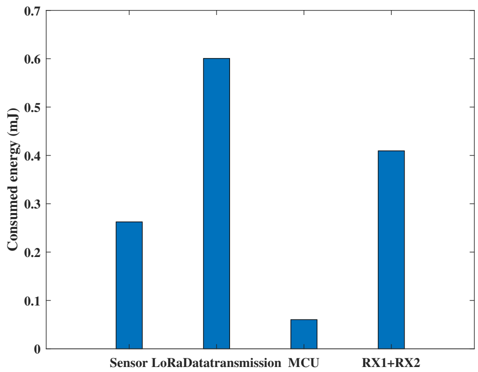

Fig. 9: Energy consumption of sensor node: Scenario 2

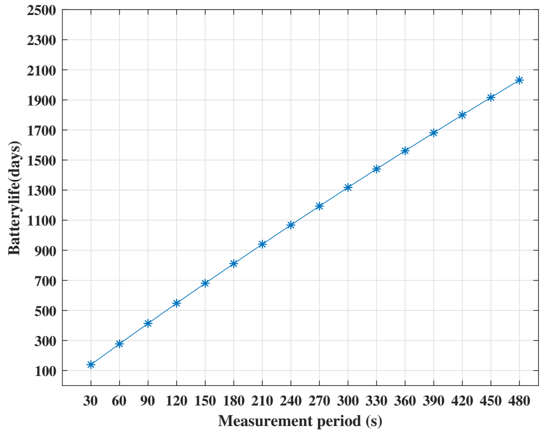

Fig. 10: Sensor node lifetime: Scenario 2

6.3 **Consumed Energy: Scenario 3**

For this scenario, we assume that the sensor node transmits data to the gateway and then receives RX1 acknowledgment excluding the RX2 acknowledgment to verify the transmission success, which means that it will consume more energy than scenario 2. The dissipated energy by the communicating sensor is given in Figure 11. We note that the consumed energy is half that consumed by the LoRa receiver Rx1 (ER = 0.21 mJ). The sensor node lifetime is illustrated in Figure 12 using the battery characteristics (capacity equals 50 mAh and a supply voltage of 3 V). The sensor node autonomy is about at 164 days when the measurement period is equal to 30 s.

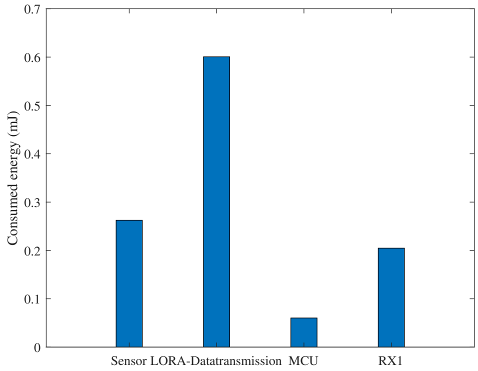

Fig. 11: Sensor node lifetime: Scenario 3

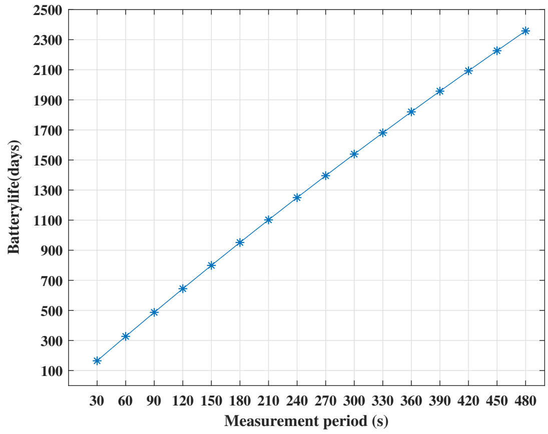

Fig. 12: Sensor node lifetime: Scenario 3

6.4 Comparison between Proposed Scenarios

According to the theoretical lifetime of an end-device is computed, employing average energy consumption results acquired for unacknowledged transmission and acknowledged transmission by using Equations (18), (19) and (20). Figure 13 and Figure 14 shows the results of energy consumption and battery life in different scenarios, respectively. The sensor node lifetime in the ideal case (data transmission with acknowledgement reception and without transmission error), so it can be concluded that the more energy is consumed from the sensors and gateways, the shorter the battery life is.

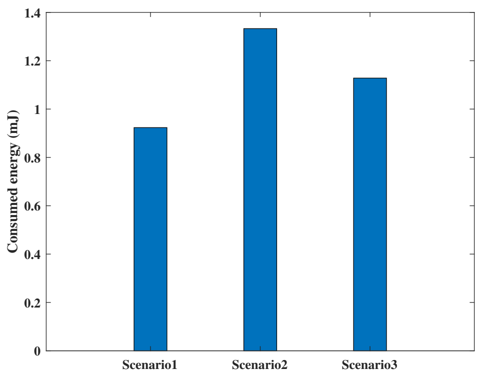

Fig. 13: Energy consumption of sensor node for all Scenarios

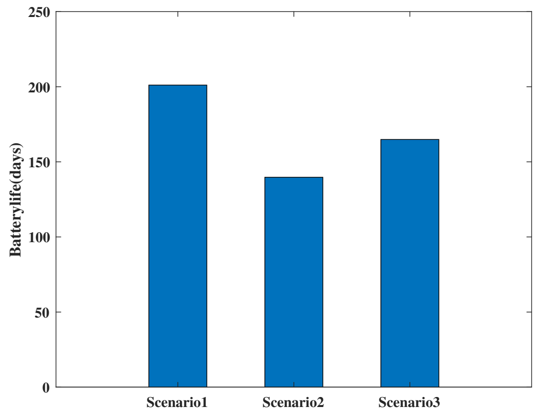

Fig. 14: Sensor node lifetime for all Scenarios

Table 4 illustrates a comparison between the proposed scenarios. As we can notice, the sensor node lifetime in Scenario 1 is higher than in Scenarios 2 and 3. These findings indicate that the energy consumption cost of receiving down-link messages from the gateway. Proportionally, SFs have a proportional relationship with average energy consumption as transmit and receive intervals of sensor nodes as a function of Bandwidth illustrated in Figures 15. However, the daily energy consumption is inversely correlated with each Bandwidth illustrated in Figures 16 as a function of SF. Furthermore, the time-on-air (ToA) increases with decreasing bit rate as function of SF. LoRaWAN network capacity can sustain millions of messages. However, the number of packets maintained in any provided deployment relies on the number of gateways that are installed. A single eight-channel gateway can support a few hundred thousand messages throughout 24 hours [50].

Table 4: Effect of Different Scenario about ACK energy consumption

Scenario	Characteristics	Energy Consumption (mJ)
Scenario 1	RX1 and RX2 not received	$E_{LRX}=0$
Scenario 2	RX1 not received; RX2 received	$E_{LRX}=0.40$
Scenario 3	RX1 received	$E_{LRX}=0.20$

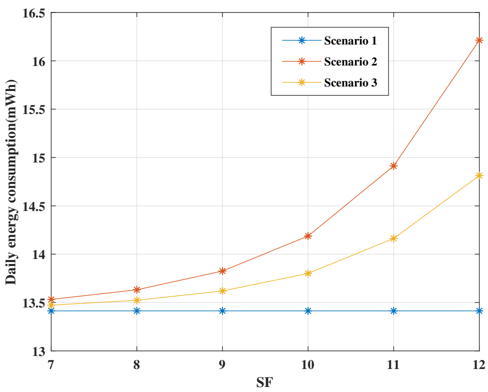

Fig. 15: Energy consumption of sensor node for all Scenarios

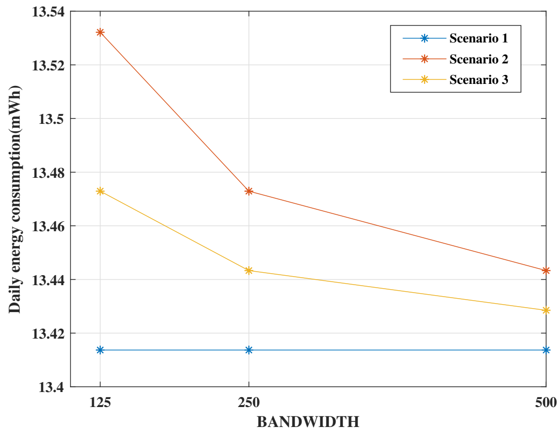

Fig. 16: Sensor node lifetime for all Scenarios

7 Result and discussion

In this section, we use the models derived in Section 5 to evaluate LoRaWAN end-device energy consumption in a different scenario, as well as the battery lifetime. As further validation of the evaluation results, we have performed the power transmission time measurements of every 8-minute, comprising several message transmissions from the end-device, for the same configurations in terms of DR, different values in terms of SF, notification period, and acknowledged or unacknowledged transmission. We have found an almost precise match between the measured energy consumption and the one computed by using the analytical models. Emphasize that this is an expected result since the analytical models have been derived based on simulation results. As shown in Figure 17 and Figure 18, the evaluation of the battery life when the power transmission is equal to 7 dBm and 17 dBm, respectively, for all scenarios. After employing the proposed model, the simulation results show the different improvements in terms of increasing the battery lifetime and decreasing the energy consumption for each scenario. To be able to evaluate the proposed model under various conditions, Figure 19 and Figure 20 presents the Battery Life for Scenario 1 and Scenario 3, when the power transmission takes distinct values. The results showed increased the energy consumption due to the rise of the power transmission time and SF values. From our obtained results, we can realize that after applying the proposed model, the improvement of increasing battery life reaches almost 259 days when the SF value is 7 for scenario 3. Table 5 describes an evaluation that gives more insights into the improvements that applied for each scenario with different values of SF and Ptr.

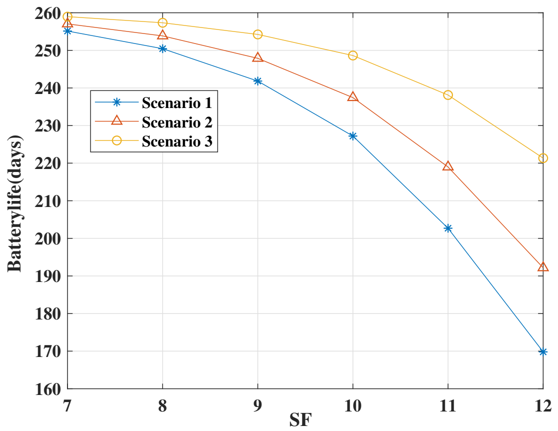

Fig. 17: Battery life when Ptr= 7 for all Scenarios

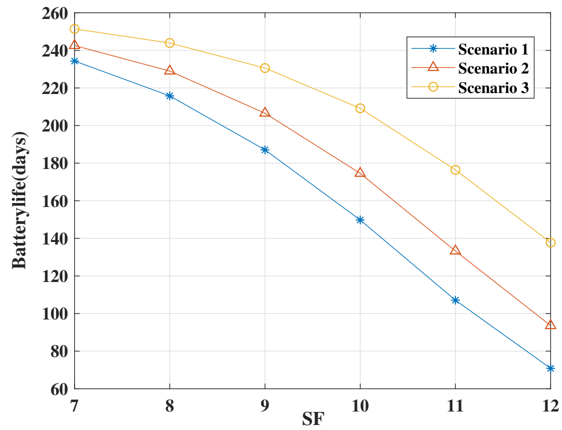

Fig. 18: Battery life when Ptr= 17 for all Scenarios

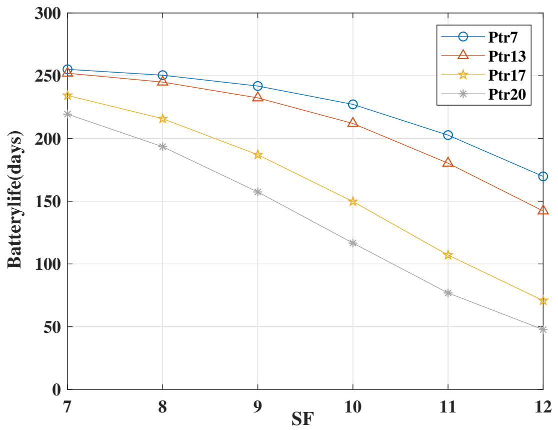

Fig. 19: Battery Life for Scenario 1 for all Power transmission values

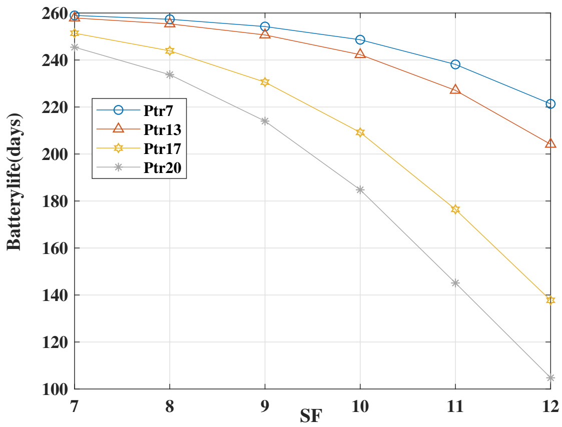

Fig. 20: Battery Life for Scenario 3 for all Power transmission values

The results in Figure 21 and Figure 22 confirmed that the consumed energy increased with the increase of the value of SF, and the power transmission. Assuming that the value of power transmission time increases from 7 dBm and 13 dBm to 17 dBm, and to 20 dBm, respectively applies to Scenario 1 and Scenario 3. This leads to the efficient use of the proposed model presented in Figure 23 and Figure 24. This minimizes the consumed energy, as well as the best Scenario, is 3 when the transmission power is 7 dBm and SF is equal to 7, so the consumed energy per days 13.51 mWh. Table 5 presents a comparison between the proposed scenarios. As we can see, the battery lifetime in Scenarios 2 and 3 is higher than in Scenario 1, because the consumed energy is less when the time of the power transmitted is lower respectively. These results show the energy consumption cost of receiving down-link messages from the gateway.

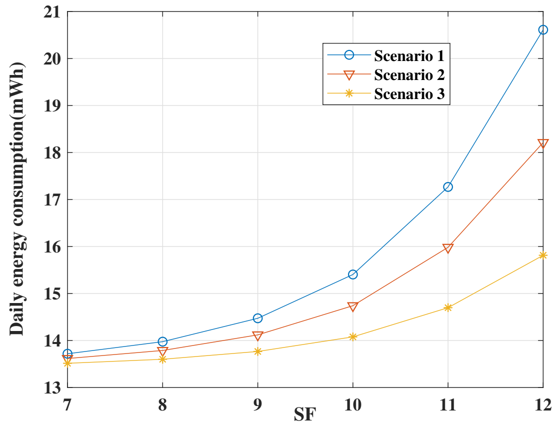

Fig. 21: Daily energy consumption for different scenario at Power transmission= 7

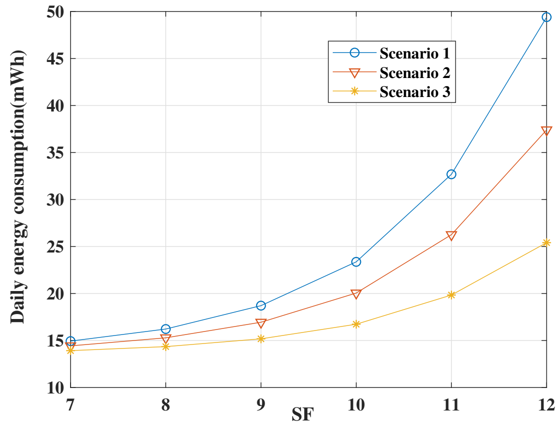

Fig. 22: Daily energy consumption for different scenario at Power transmission= 17

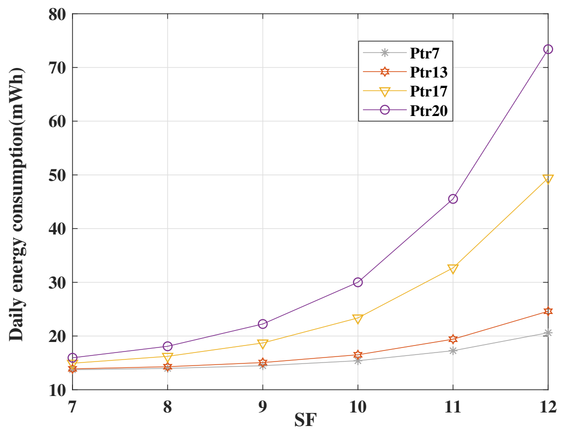

Fig. 23: Daily Energy Consumption for Scenario 1 at different power transmission

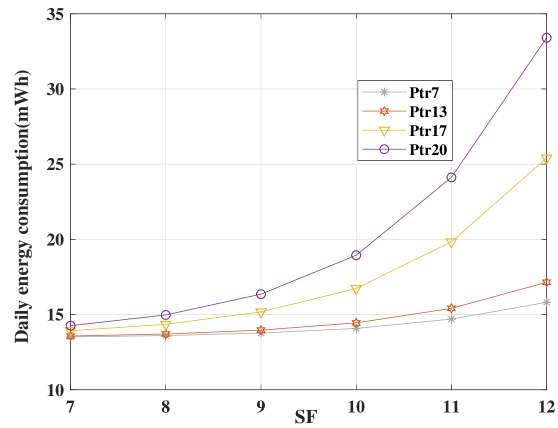

Fig. 24: Daily Energy Consumption for Scenario 3 at different power transmission

Table 5: Summary of Energy consumption and Battery Life time

Scenarios	Transmission Power (dBm)	SF	Energy consumption per day(mWh)	Battery life time (days)
Scenario 1	7	7	13.71	255.1
		8	13.97	250.4
		9	14.47	241.8
		10	15.40	227.2
		11	15.98	202.7
		12	18.21	169.8
	17	7	14.93	234.3
		8	16.22	215.8
		9	18.70	187.0
		10	23.36	149.7
		11	32.28	107.1
		12	49.40	70.8
Scenario 2	7	7	13.61	257.0
		8	13.78	253.8
		9	14.11	247.9
		10	14.74	237.4
		11	15.98	218.9
		12	18.21	192.2
	17	7	14.42	242.6
		8	15.28	228.9
		9	16.94	206.56
		10	20.04	174.6
		11	26.26	133.3
		12	37.40	93.6
Scenario 3	7	7	13.51	258.9
		8	13.60	257.3
		9	13.76	254.2
		10	14.07	248.6
		11	14.69	238.1
		12	15.81	221.3
	17	7	13.92	251.4
		8	14.34	243.9
		9	15.18	230.6
		10	16.73	209.2
		11	19.84	176.4
		12	25.41	137.7

To show the effect of different time interval when we send periodic messages on the daily energy consumption and battery lifetime, we refer to Figure 25 and Figure 26 . We note that the energy consumption of the node depends on how often we are transmitting the message per day (it increases with frequency and SF).

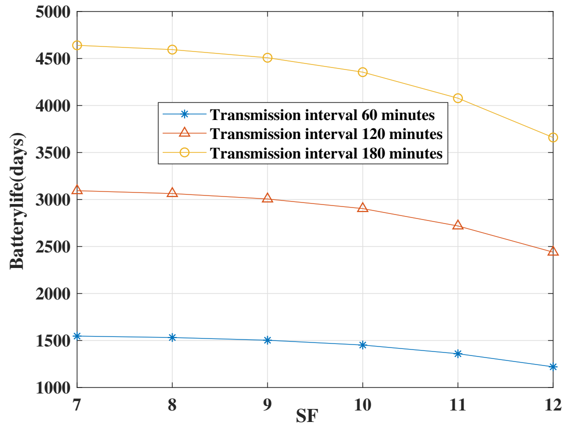

Fig. 25: Battery Life time for different time

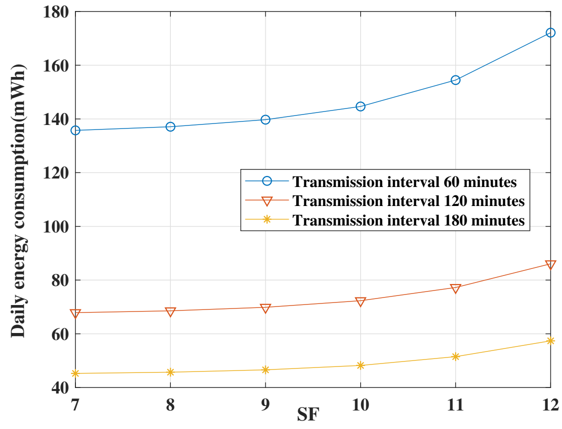

Fig. 26: Daily energy consumption for different time

8 Conclusion

To intercommunicate over long distances using minimal energy is an intricate task. LPWANs attain this by constructing star topology networks, that permit devices to communicate directly with a gateway without any relaying of messages. By employing slow and straightforward modulation techniques, LPWA devices operate efficiently to have a high energy per bit, accordingly, a strong signal. The most standard carrier waves in LPWANs are Narrowband waveforms that modulate a limited bandwidth that will emerge as a peak and Spread waveforms that distribute the signal out and later retrieve it utilising post-processing techniques. A common factor for them all is that they have a low protocol overhead.

Energy consumption is one of the main objectives in the procedure of designing and development of sensor network. In this research work, we consider the energy consumption of Class A model that has been presented for dense LoRaWAN network viewing the information transmitted at periodic intervals between the end nodes and gateways in confirmed and unconfirmed transmission. We presented thorough numerical results that the average energy consumption in acknowledged and unacknowledged transmission through proposing different LoRaWAN scenarios. To evaluate the energy consumption of the sensor node, we concluded that receiving a transmission acknowledgement consumes an energy amount which reduces the sensor node lifetime. Moreover, changes with different LoRa/LoRaWAN parameters such as spreading factor, coding rate, payload size and bandwidth. Optimizing these parameters is essential to decrease the energy consumption of the sensor node. The proposed sensor node operating on 50 mAh battery that transmits one message to gateway every 30 sec with the higher spreading factor (SF) can have a theoretical lifetime of up to 2.78 years as compared to 4.4 years for lower SF.

Finally, the energy efficiency of the LoRaWAN network is studied concerning the specific average number of nodes. Furthermore, we illustrated the superiority of lower over higher spreading factor in terms of energy efficiency over a circular coverage area. The optimal trade-off between power consumption and other device parameters relies on the specific application and use case. The results of this research paper could be used to understand the relationship between device variables and power consumption. The future works could be, the energy model is further investigate used the choice of the antenna and how it can affect the range and the reliability. Also, investigation of co-existence between narrowband and spread wave technologies is an important topic for future research. Additional elements could be added to the proposed model, such as processing power based on the operating frequency to maximize the sensor node lifetime.

9 Abbreviation

Internet of Things (IoT), Low-Power Wide Area Network (LPWAN), radio-frequency identification (RFID), Quick Response (QR), machine-type communications (MTC), Chirp Spreading Spectrum (CSS), coding rate (CR), bandwidth (BW), the network server (NS), spreading factor(SF), the time-on-air (ToA), Carrier Frequency (CF), packet error rate (PER), the number of payload symbols (N_{Pload}), number of payload bytes (PL), cyclic redundancy check (CRC), the number of preamble symbols ($n_{preamble}$), the packet duration (t_{packet}), the transmission power consumption (P_{TX}), the energy consumption per transmission (E_{packet}), the number of data transfers per day (N_{msg}), the current sending cycle (T_C), analog to digital converter (ADC), central processing unit(CPU), The total consumed energy (E_{TOTAL}), the energy consumed when the system is active (E_{Active}), the energy consumed when the system is in sleep mode (E_{Sleep}), the power consumption in sleep mode (P_{Sleep}), the duration in sleep mode (t_{Sleep}), the lifetime of the devices (LT), the battery capacity (E_{Bat}), the energy consumption per day (E_{day}), the number of transactions (n_{msg}), the battery capacity ($C_{Battery}$), the battery life (D_{BL}).

Declaration

Availability of data and materials

The data used to support the findings of this study are available from the corresponding author upon request.

Competing interests

The authors declare that they have no competing interests.

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Authors contributions

HR as the principal investigator takes the primary responsibility for this research and analyzed the results. All authors read and approved the final manuscript. TB conceived of the study, and participated in its design and coordination and helped to draft the manuscript.

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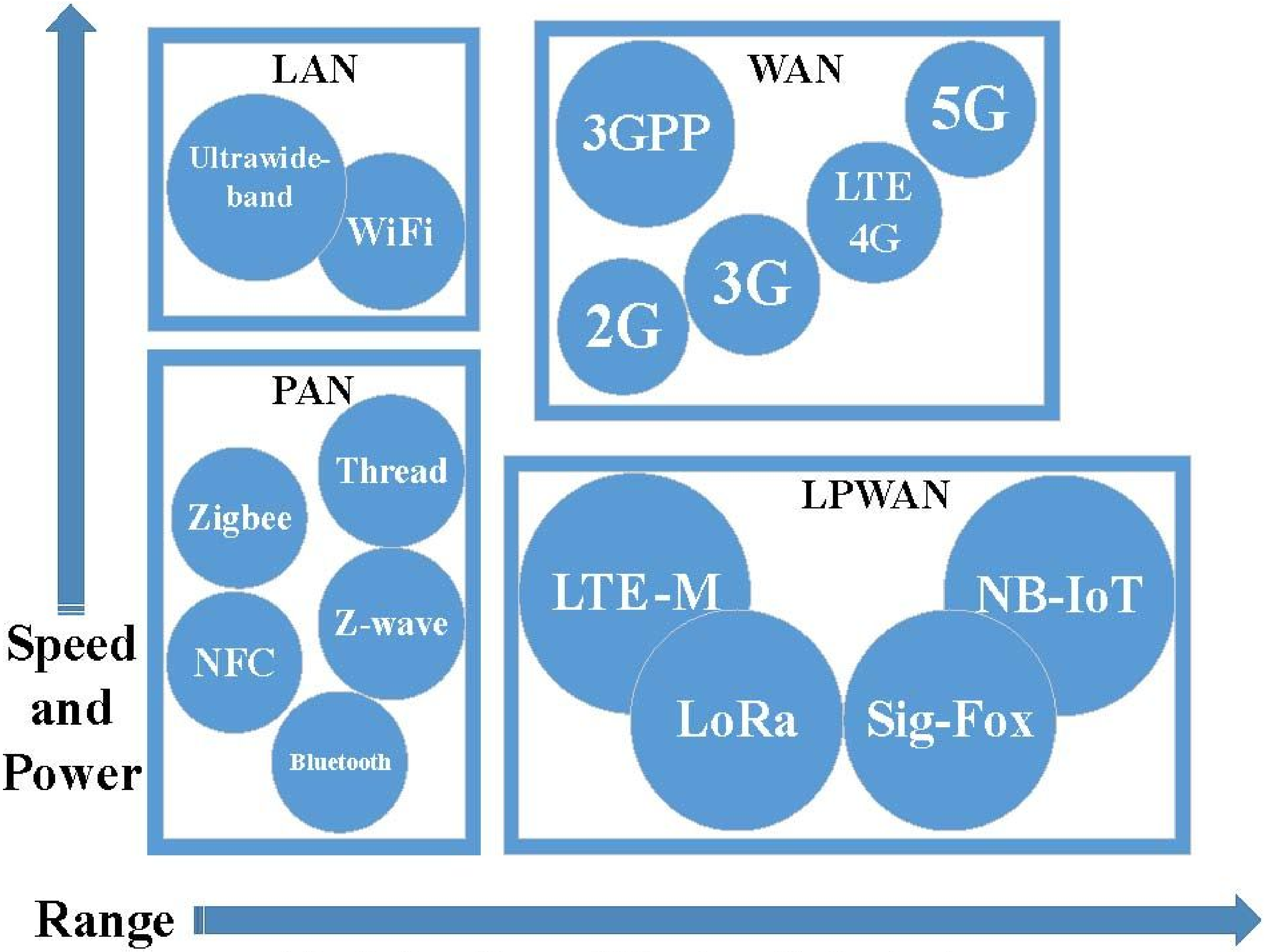

Fig. 1: Low Power Wide Area Technologies

Figure 1

Low Power Wide Area Technologies

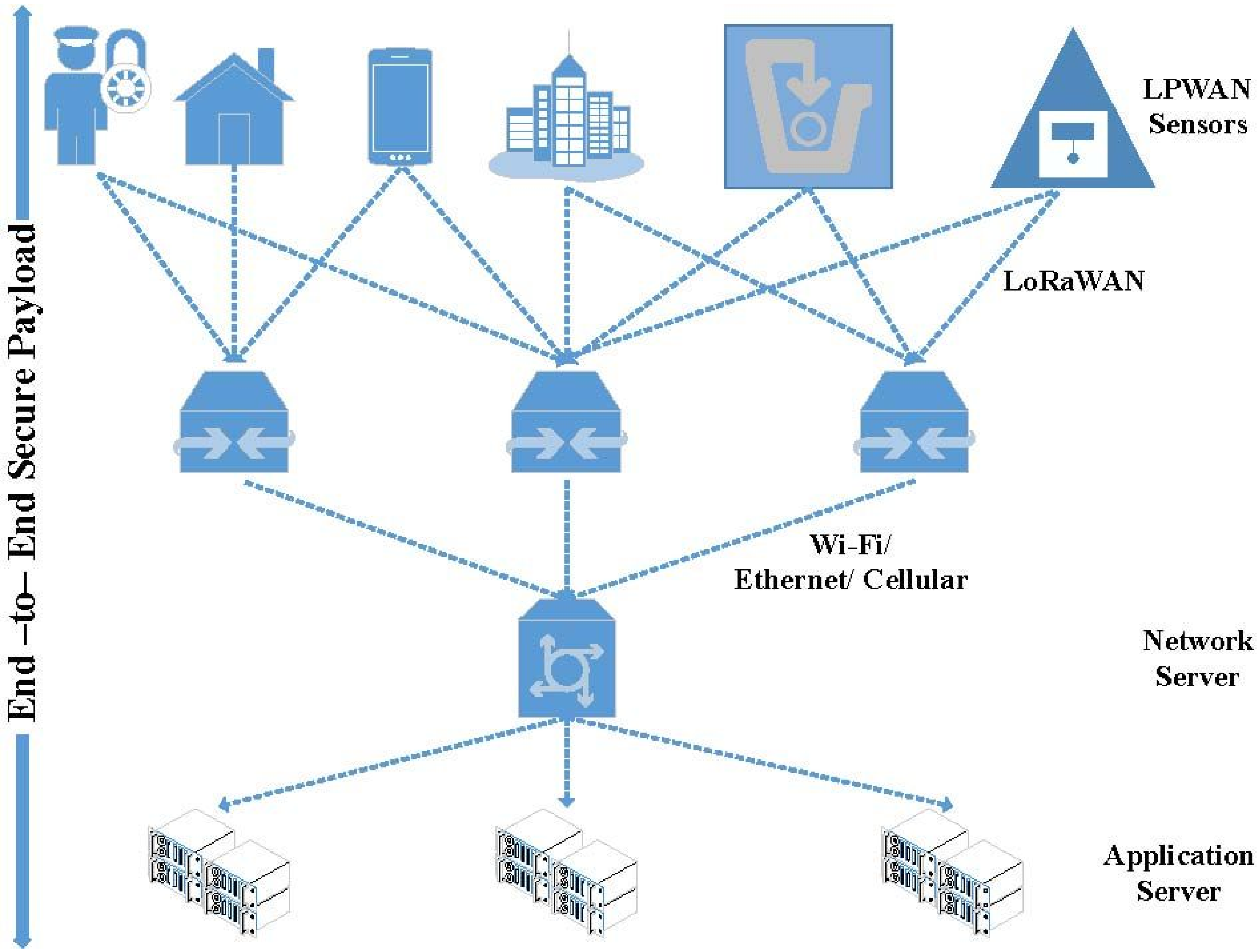

Figure 2

LoRa Network Architecture

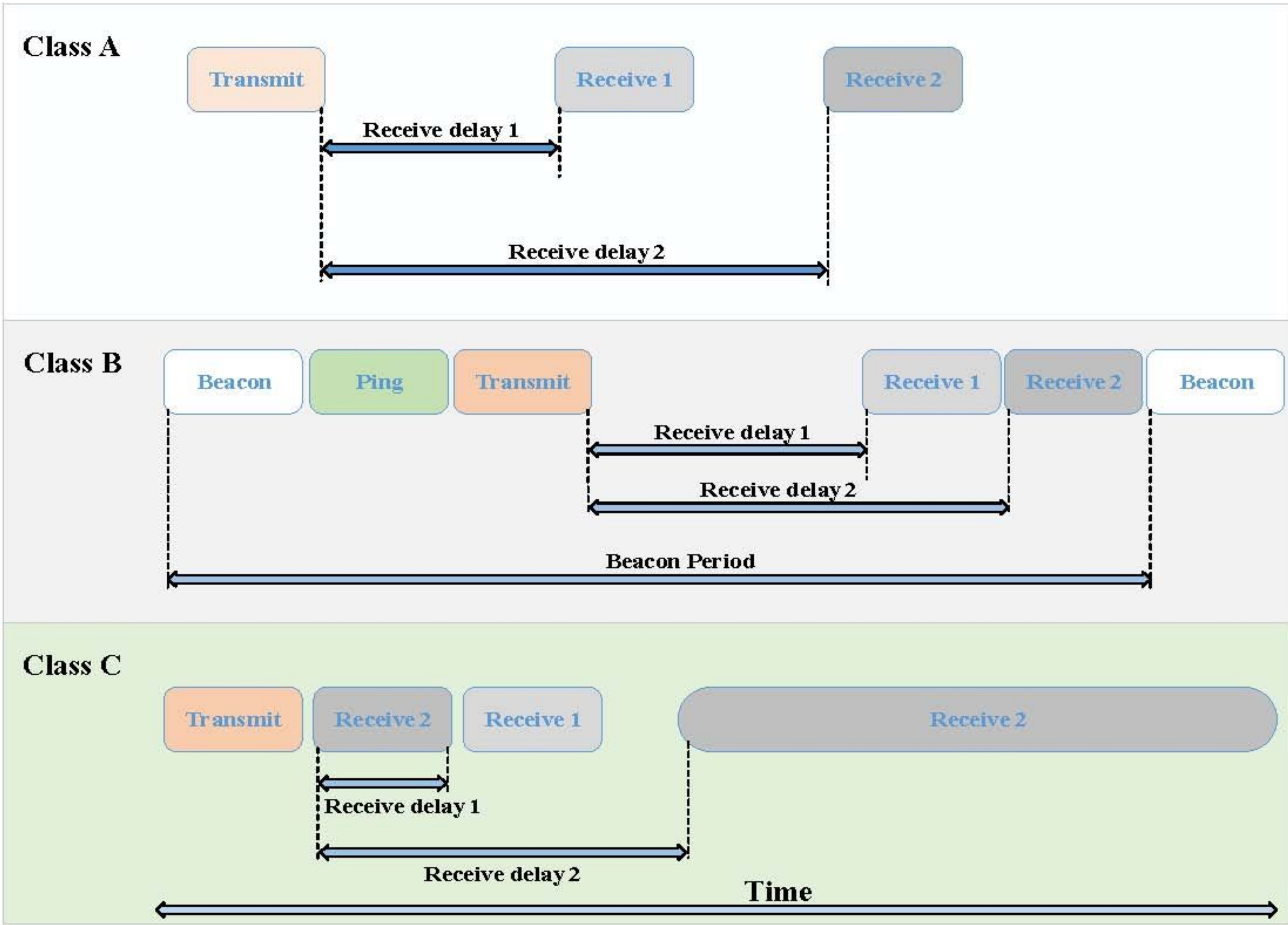

Figure 3

Device classes in LoRa

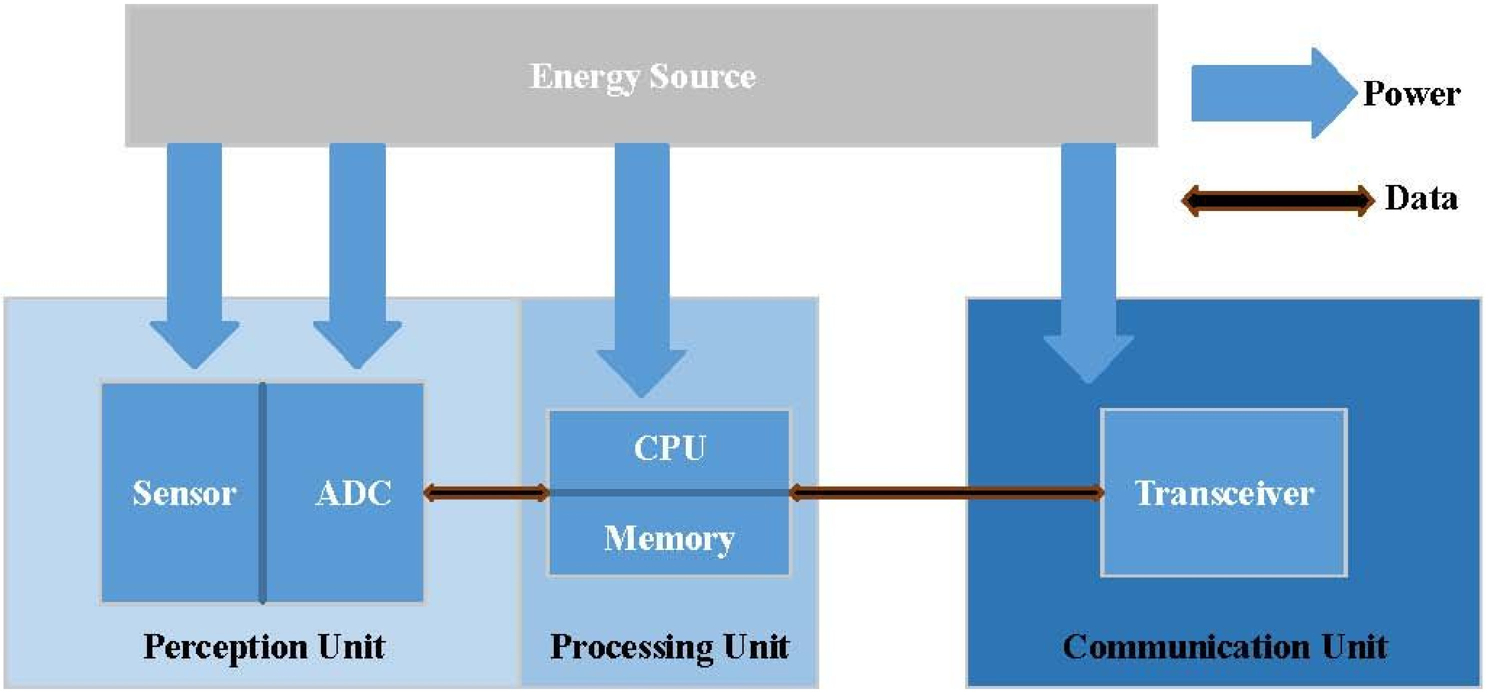

Figure 4

Senor node

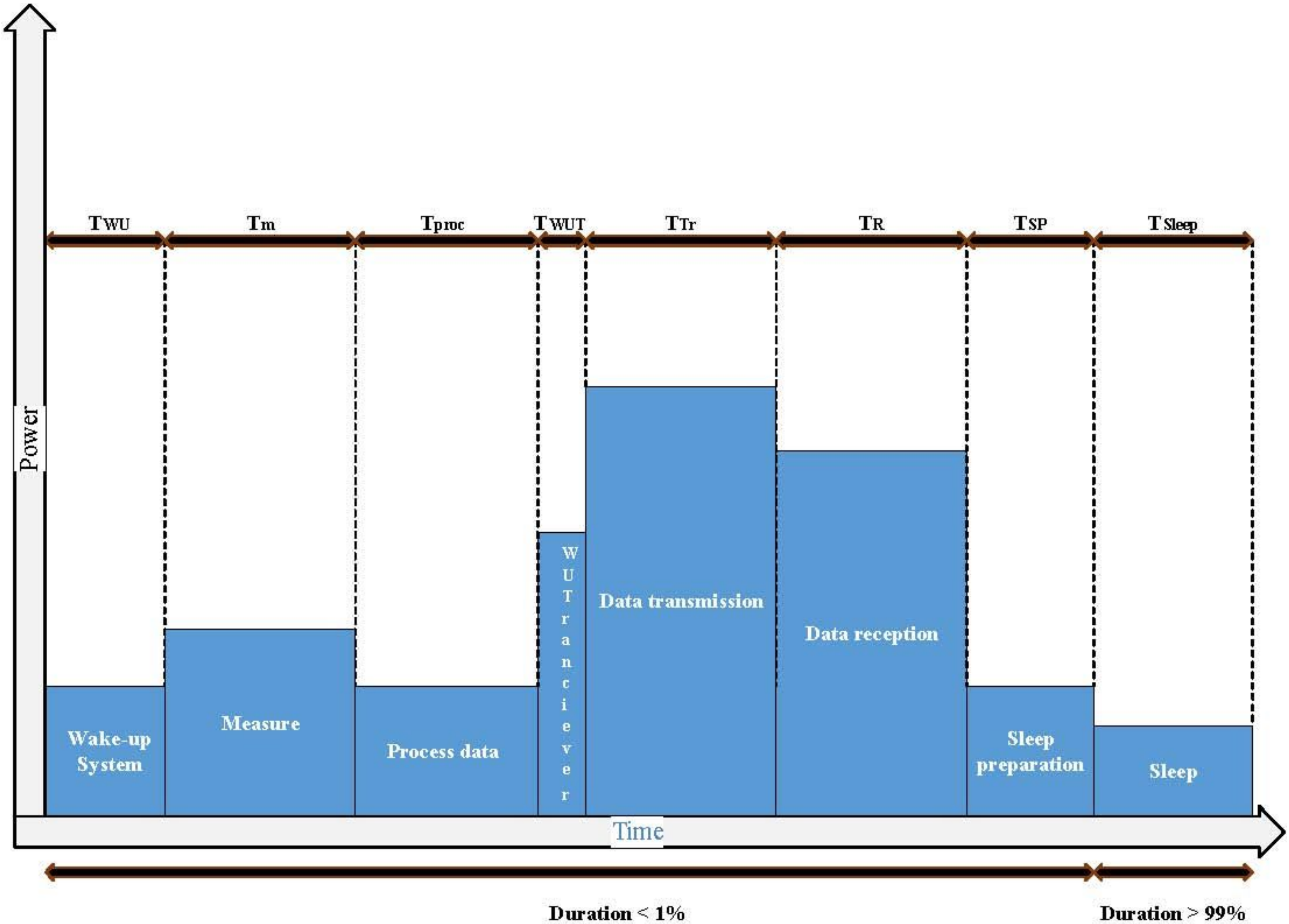

Fig. 5: General state-based energy consumption model

Figure 5

General state-based energy consumption model

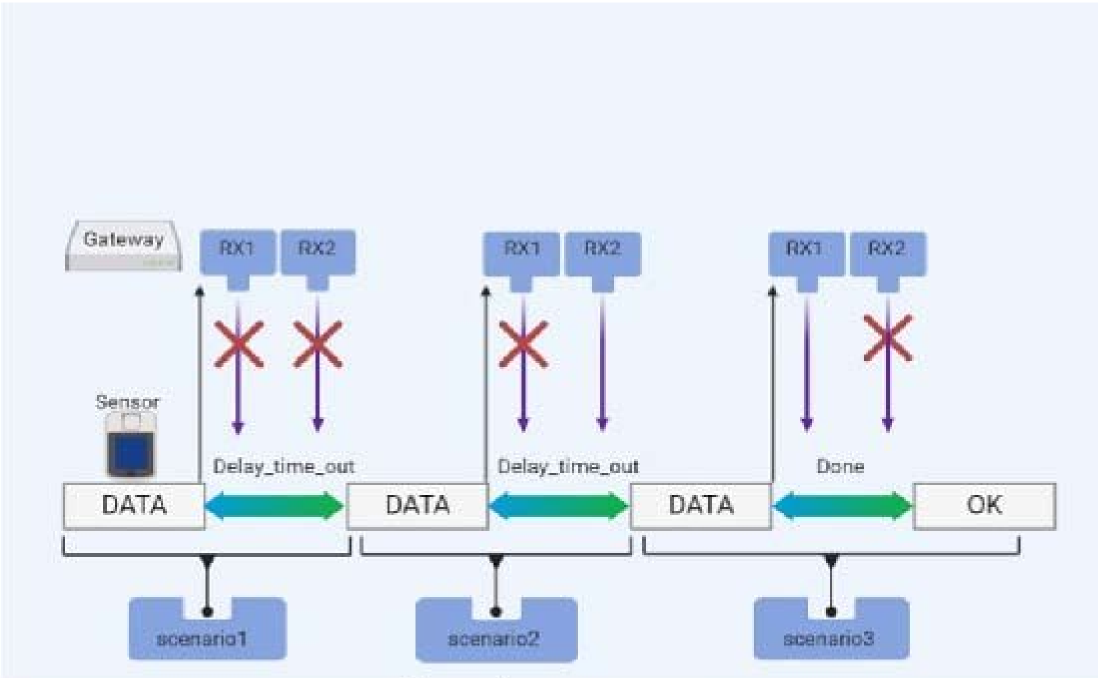

Fig. 6: Sensor scenarios

Figure 6

Sensor scenarios

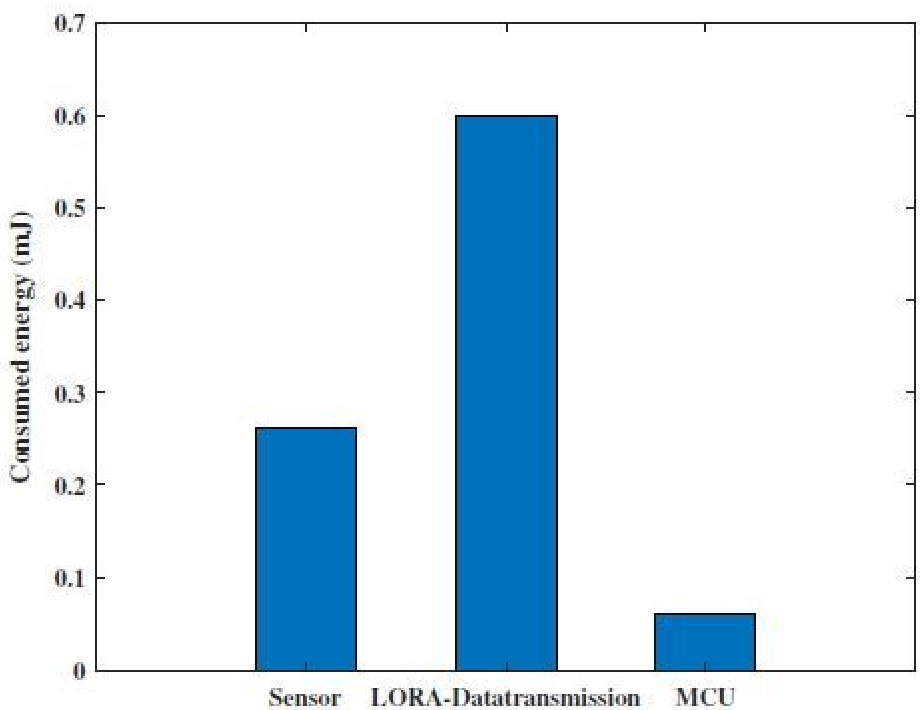

Figure 7

Energy consumption of sensor node: Scenario 1

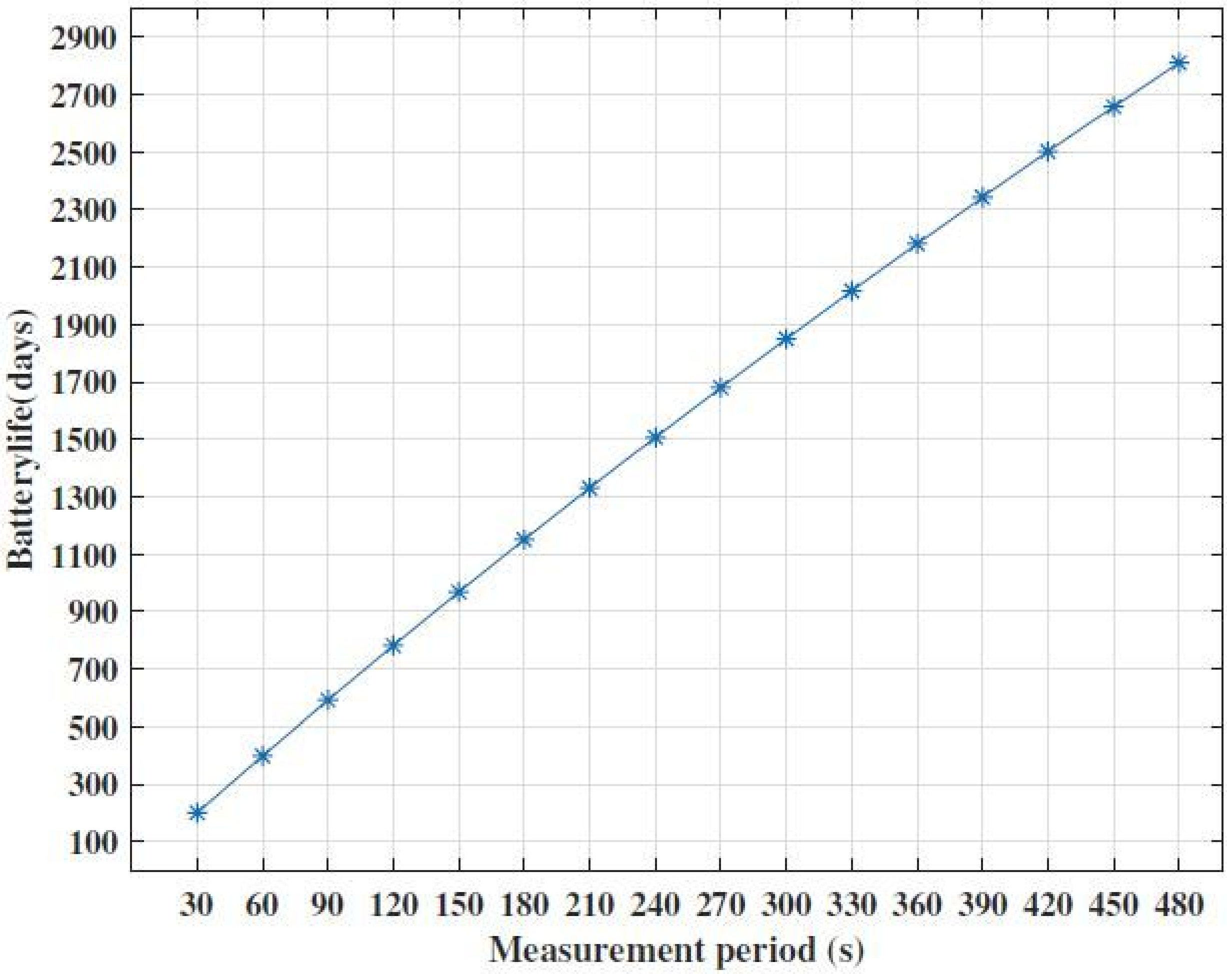

Figure 8

Sensor node lifetime: Scenario 1

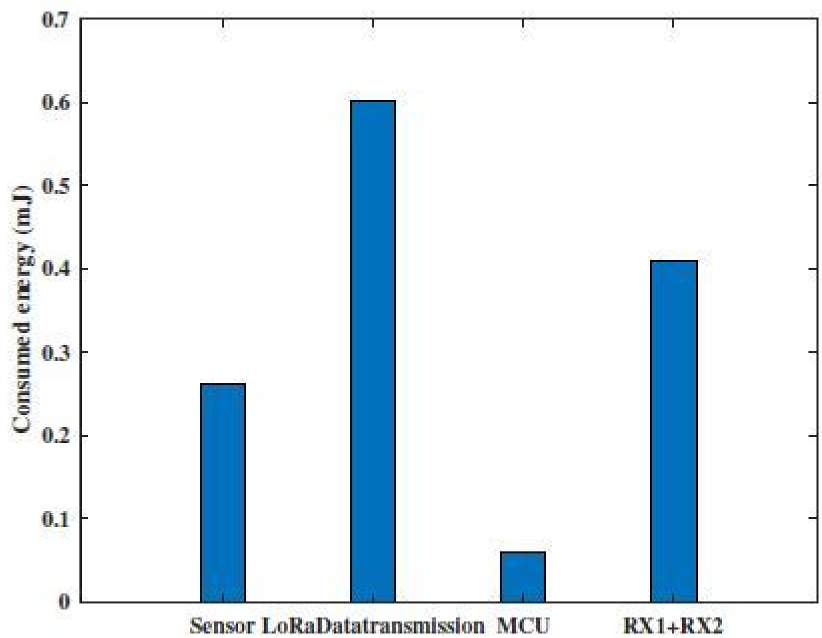

Figure 9

Energy consumption of sensor node: Scenario 2

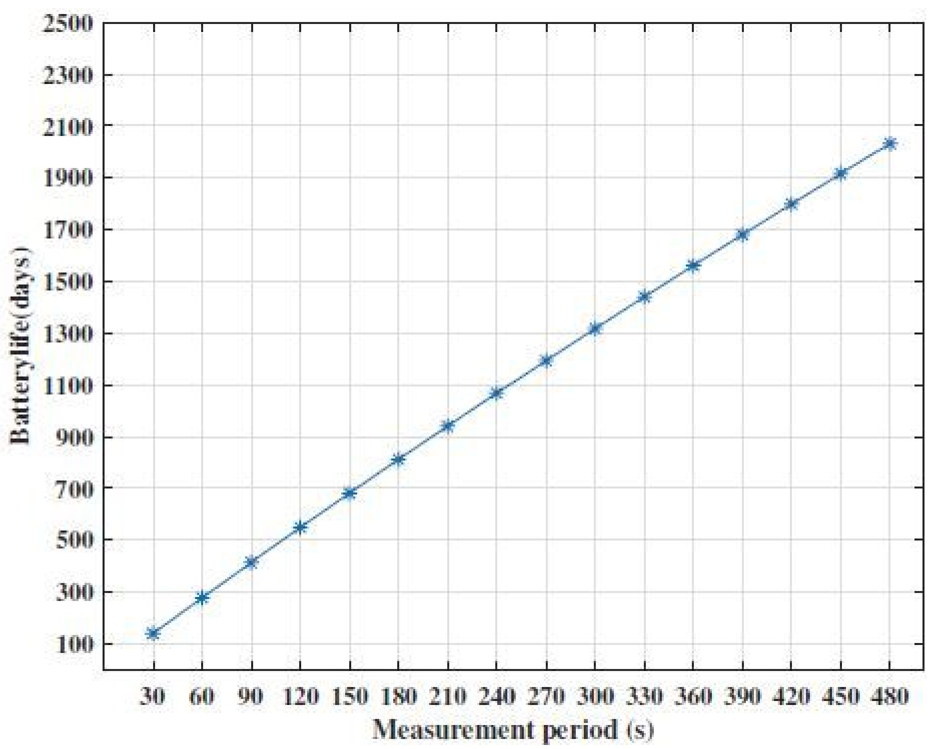

Figure 10

Sensor node lifetime: Scenario 2

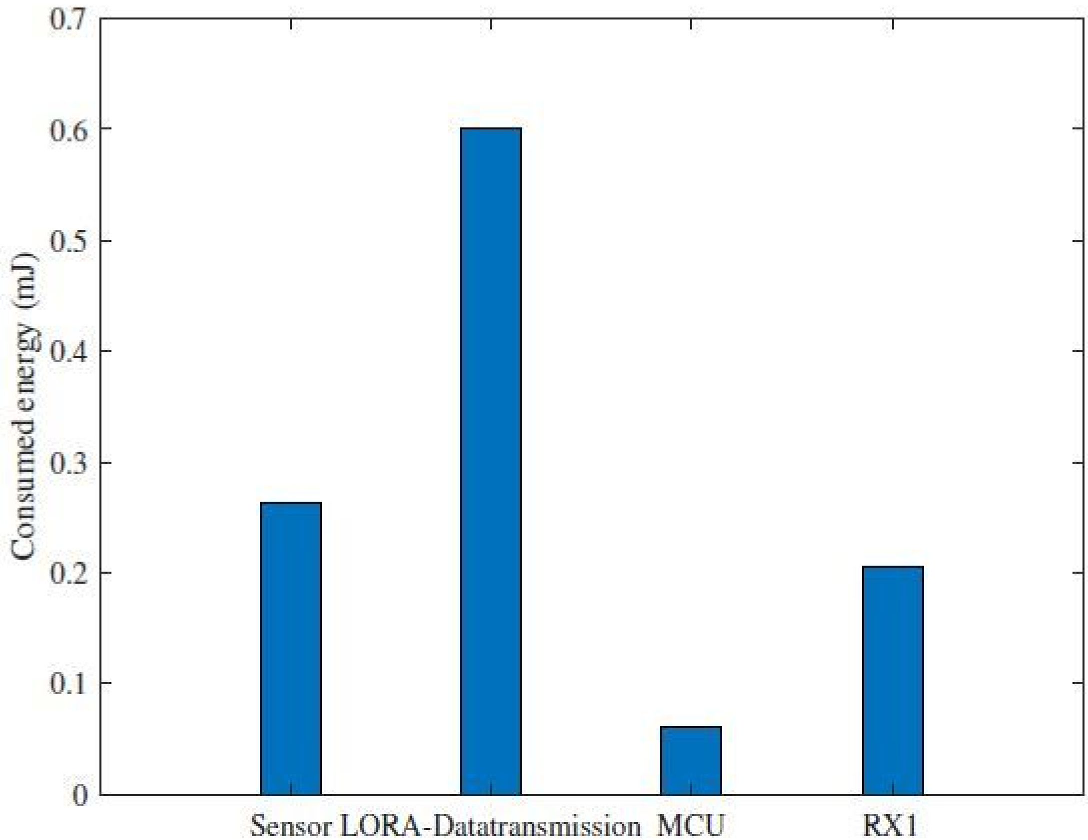

Figure 11

Sensor node lifetime: Scenario 3

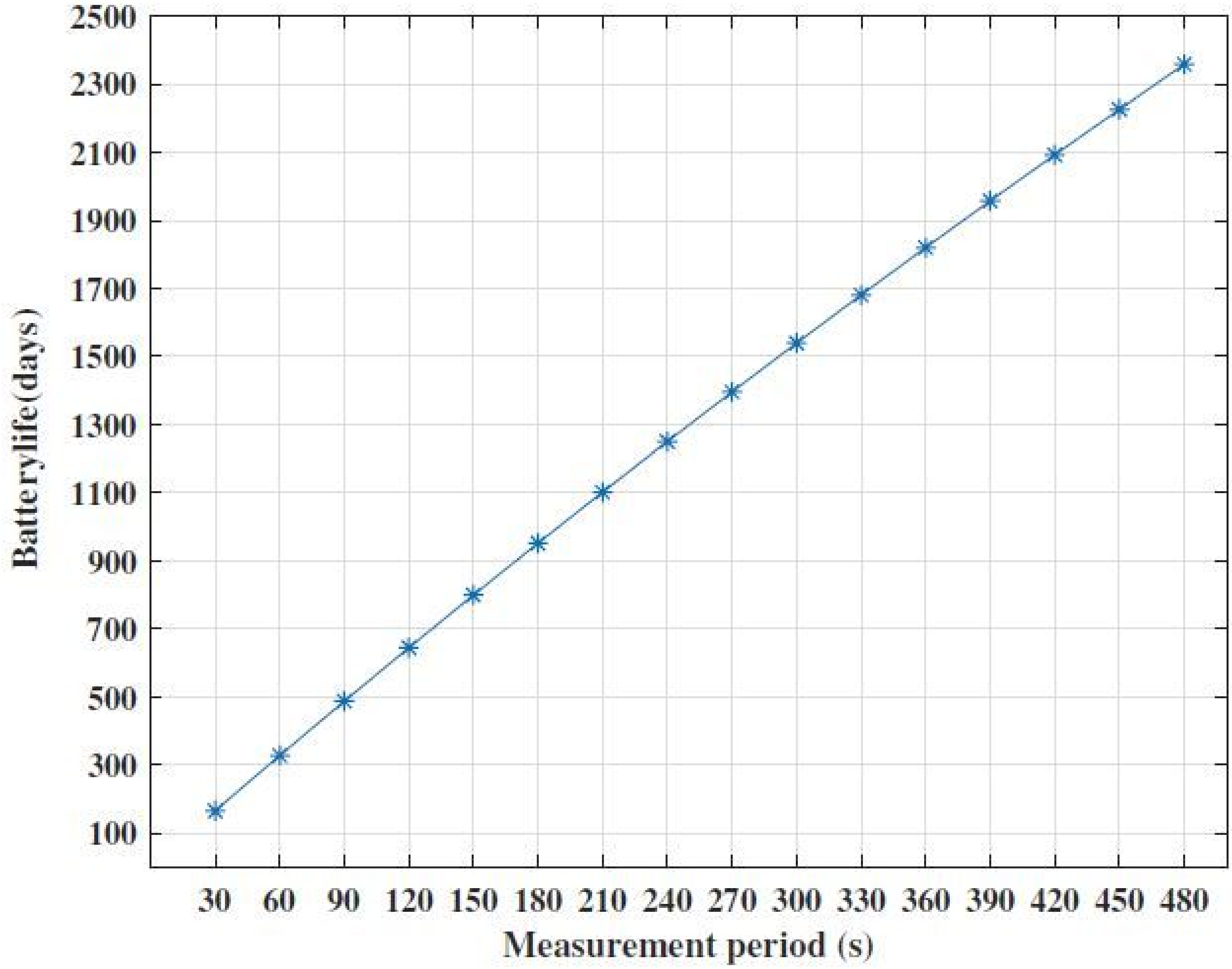

Figure 12

Sensor node lifetime: Scenario 3

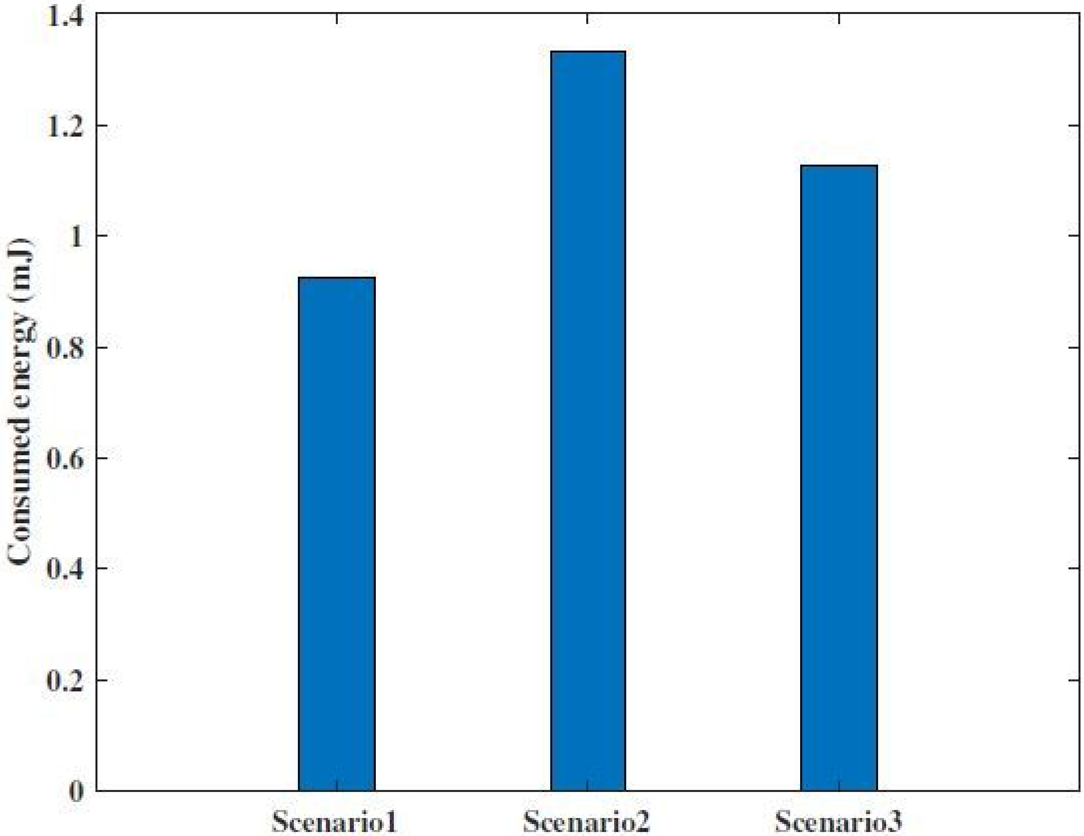

Figure 13

Energy consumption of sensor node for all Scenarios

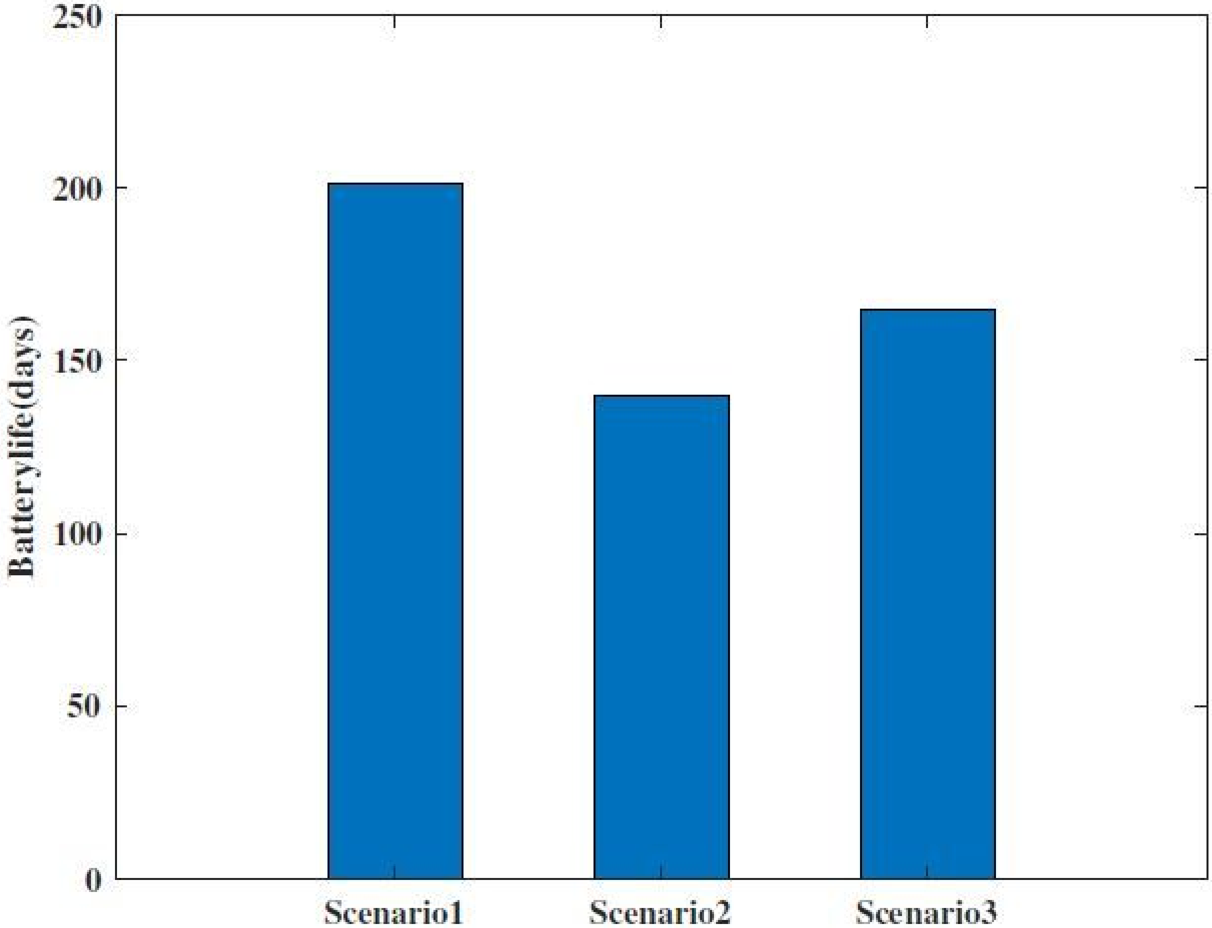

Figure 14

Sensor node lifetime for all Scenarios

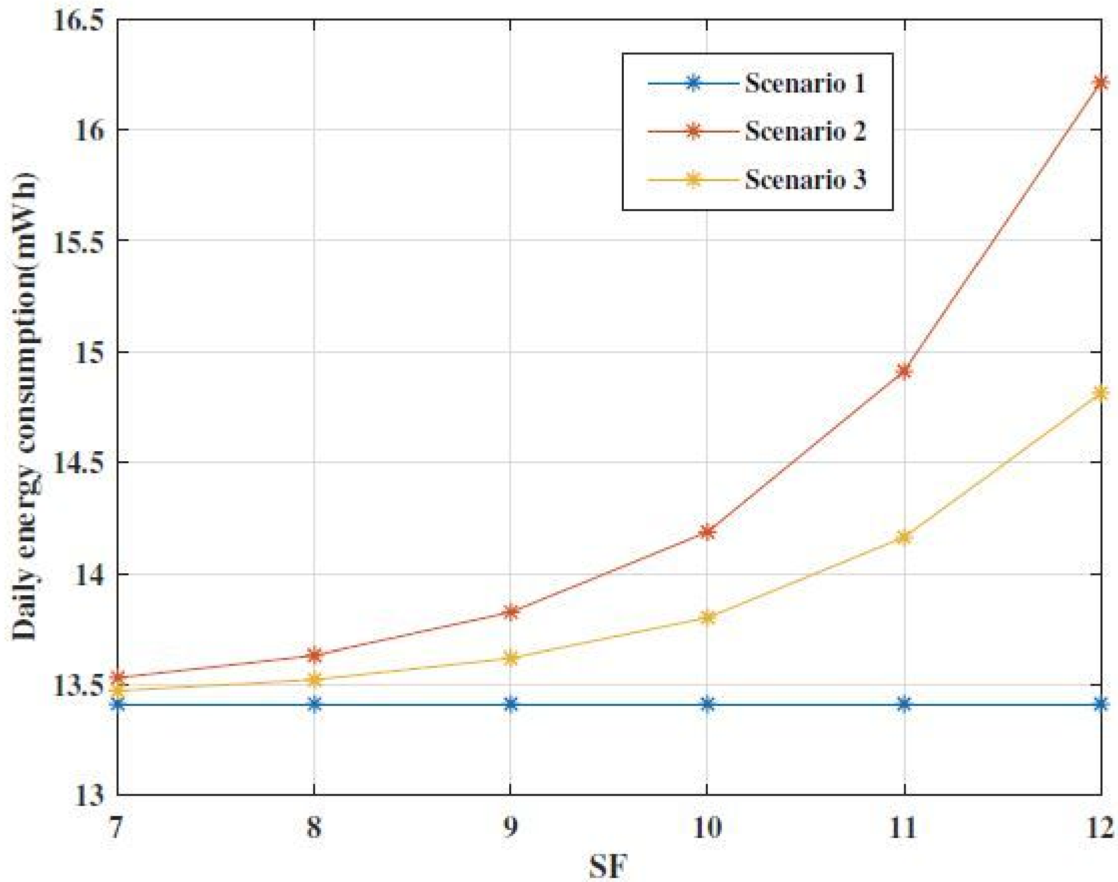

Figure 15

Energy consumption of sensor node for all Scenarios

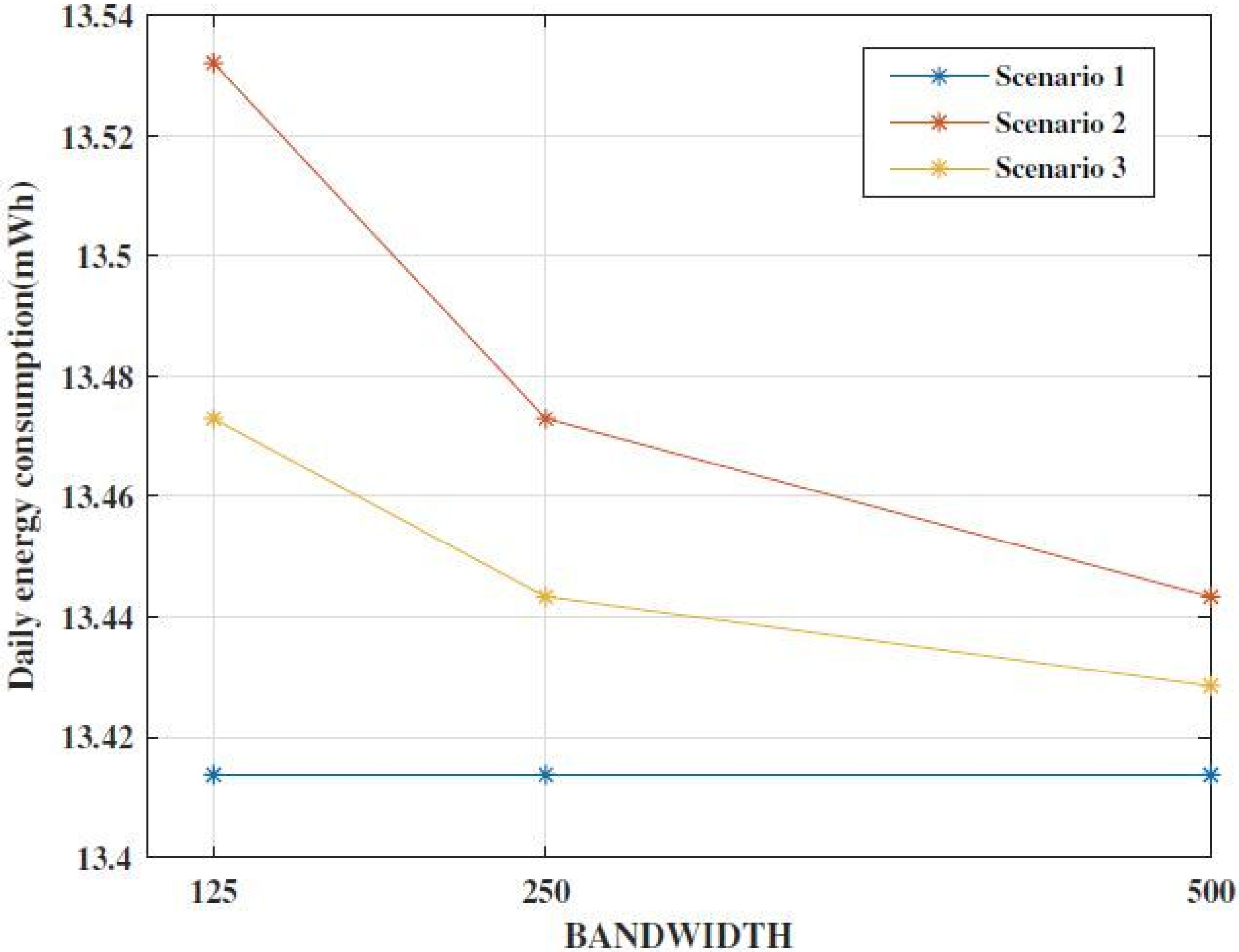

Figure 16

Sensor node lifetime for all Scenarios

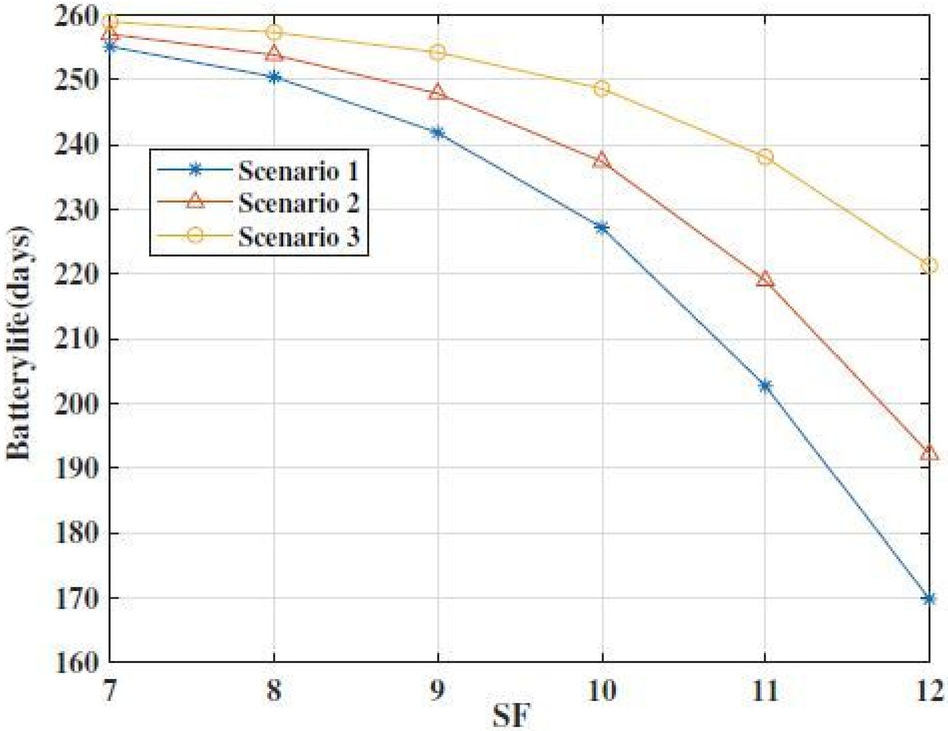

Figure 17

Battery life when Ptr= 7 for all Scenarios

Figure 18

Battery life when Ptr= 17 for all Scenarios

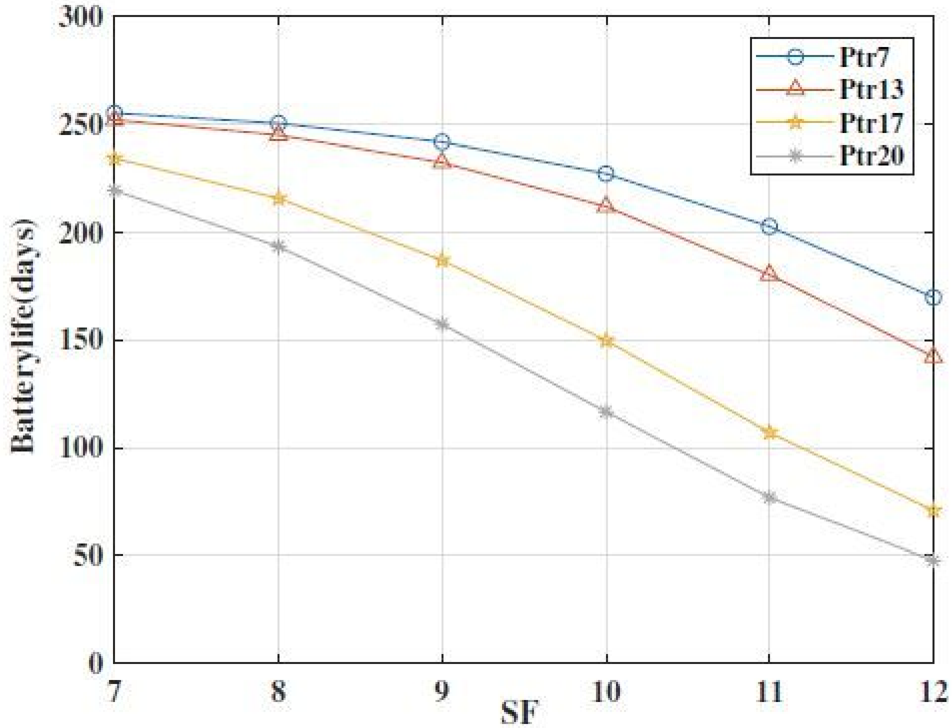

Figure 19

Battery Life for Scenario 1 for all Power transmission values

Figure 20

Battery Life for Scenario 3 for all Power transmission values

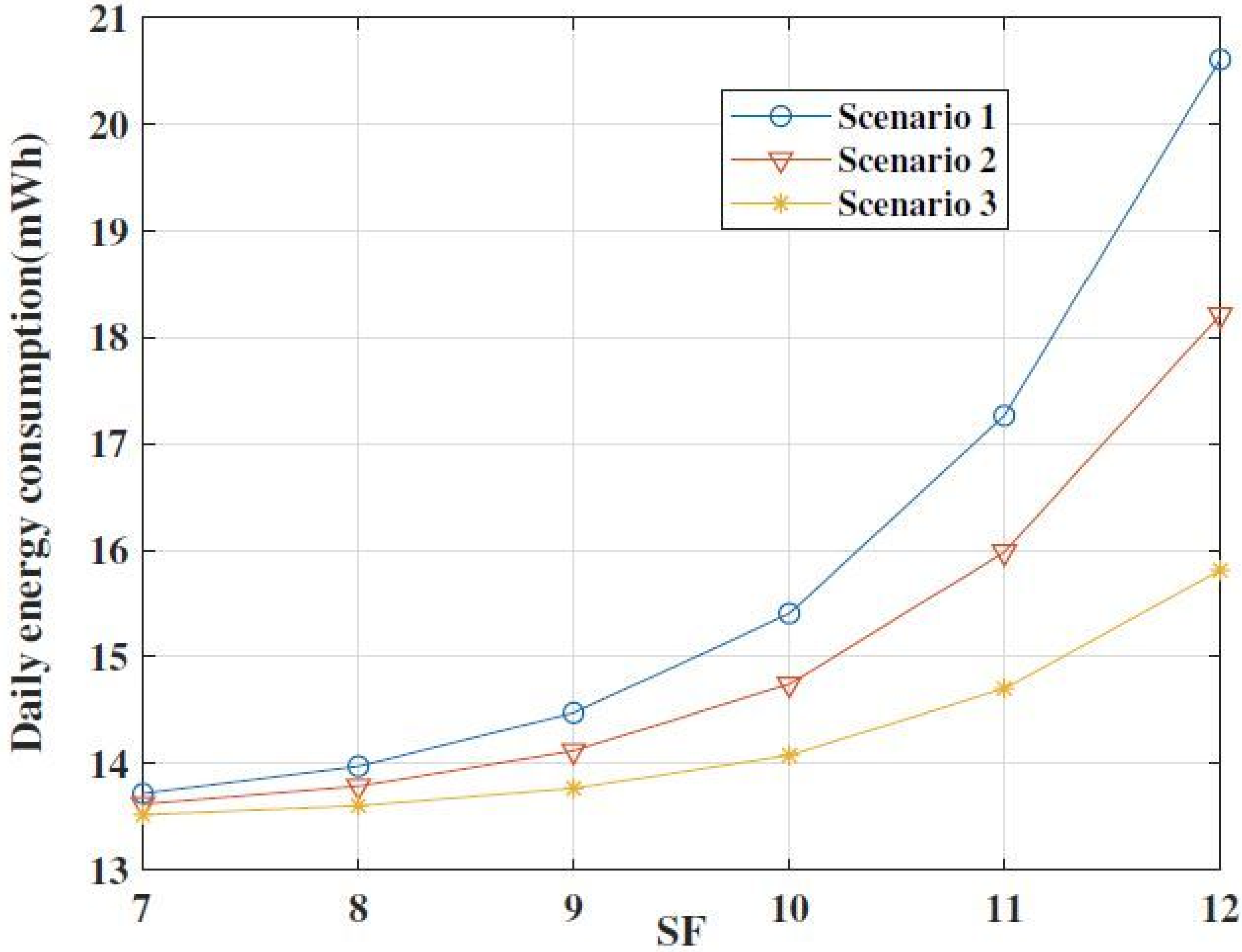

Figure 21

Daily energy consumption for different scenario at Power transmission= 7

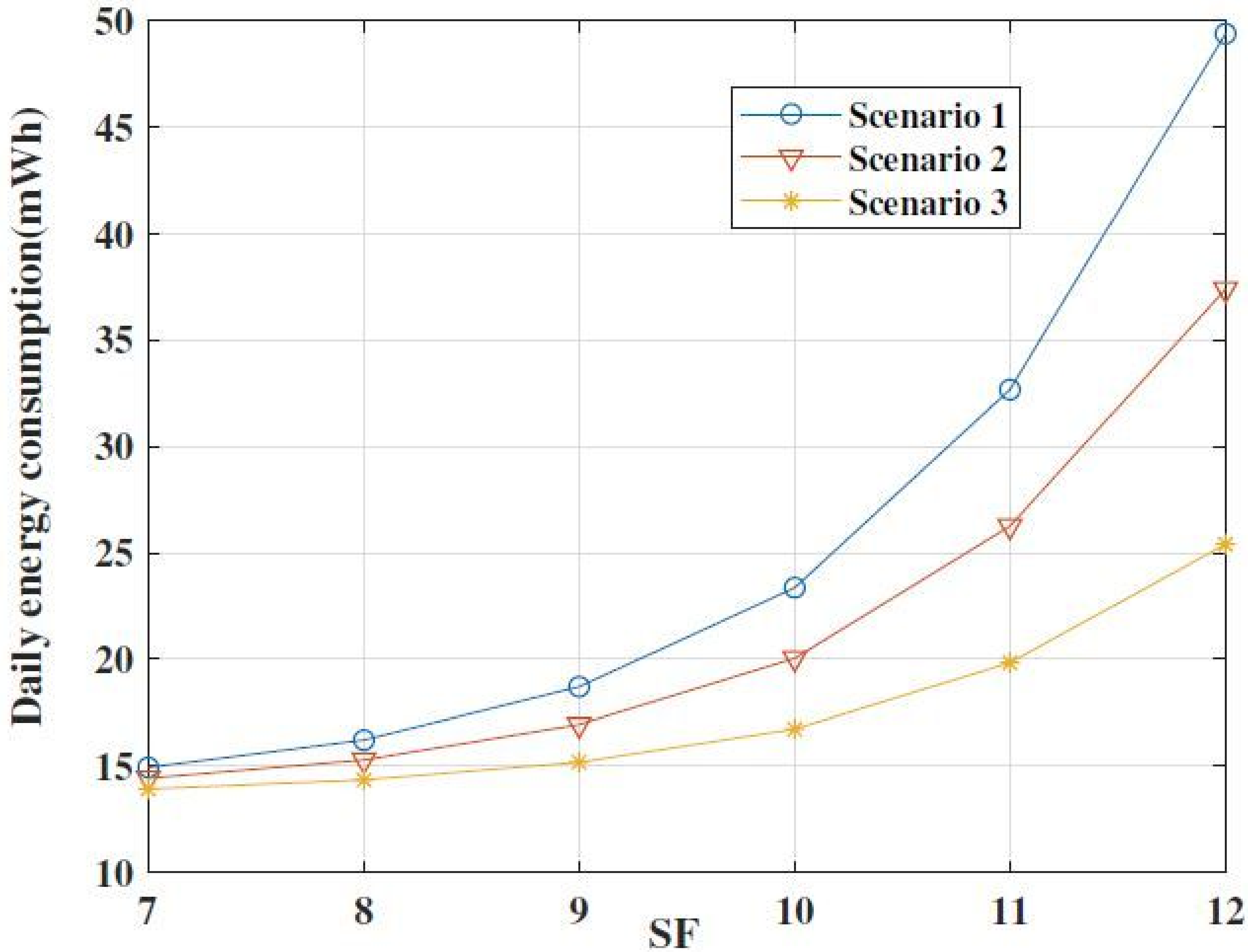

Figure 22

Daily energy consumption for different scenario at Power transmission= 17

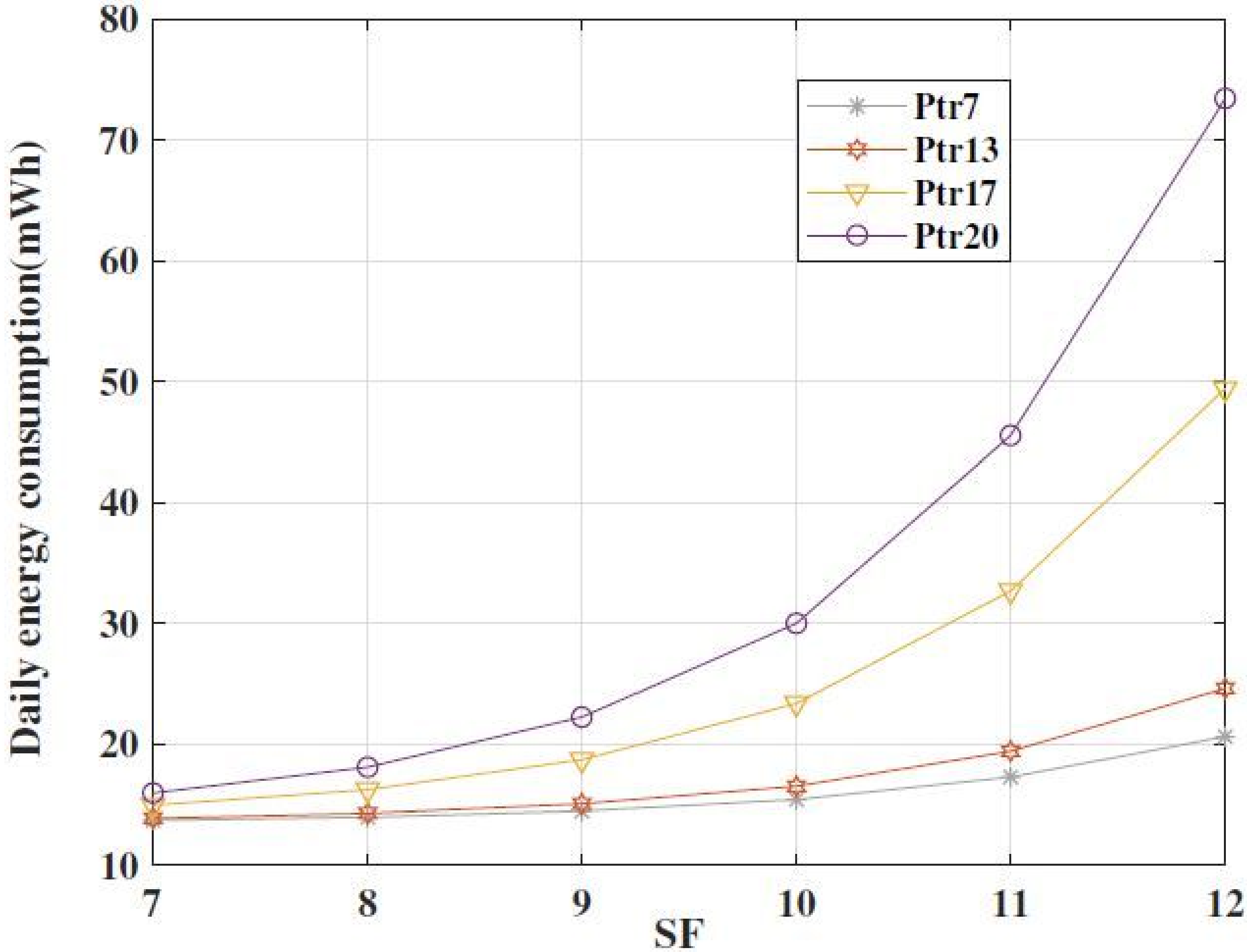

Figure 23

Daily Energy Consumption for Scenario 1 at different power transmission

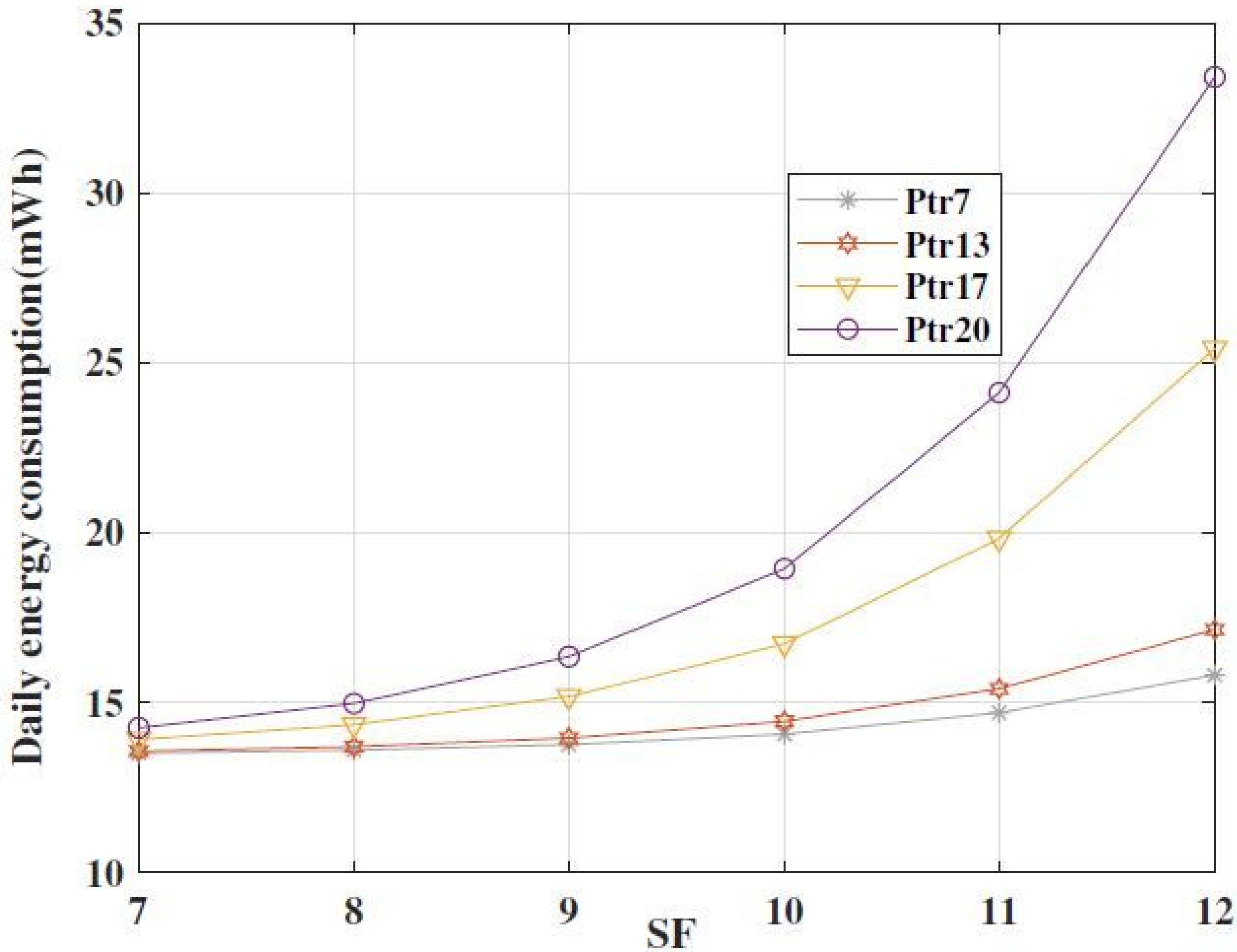

Figure 24

Daily Energy Consumption for Scenario 3 at different power transmission

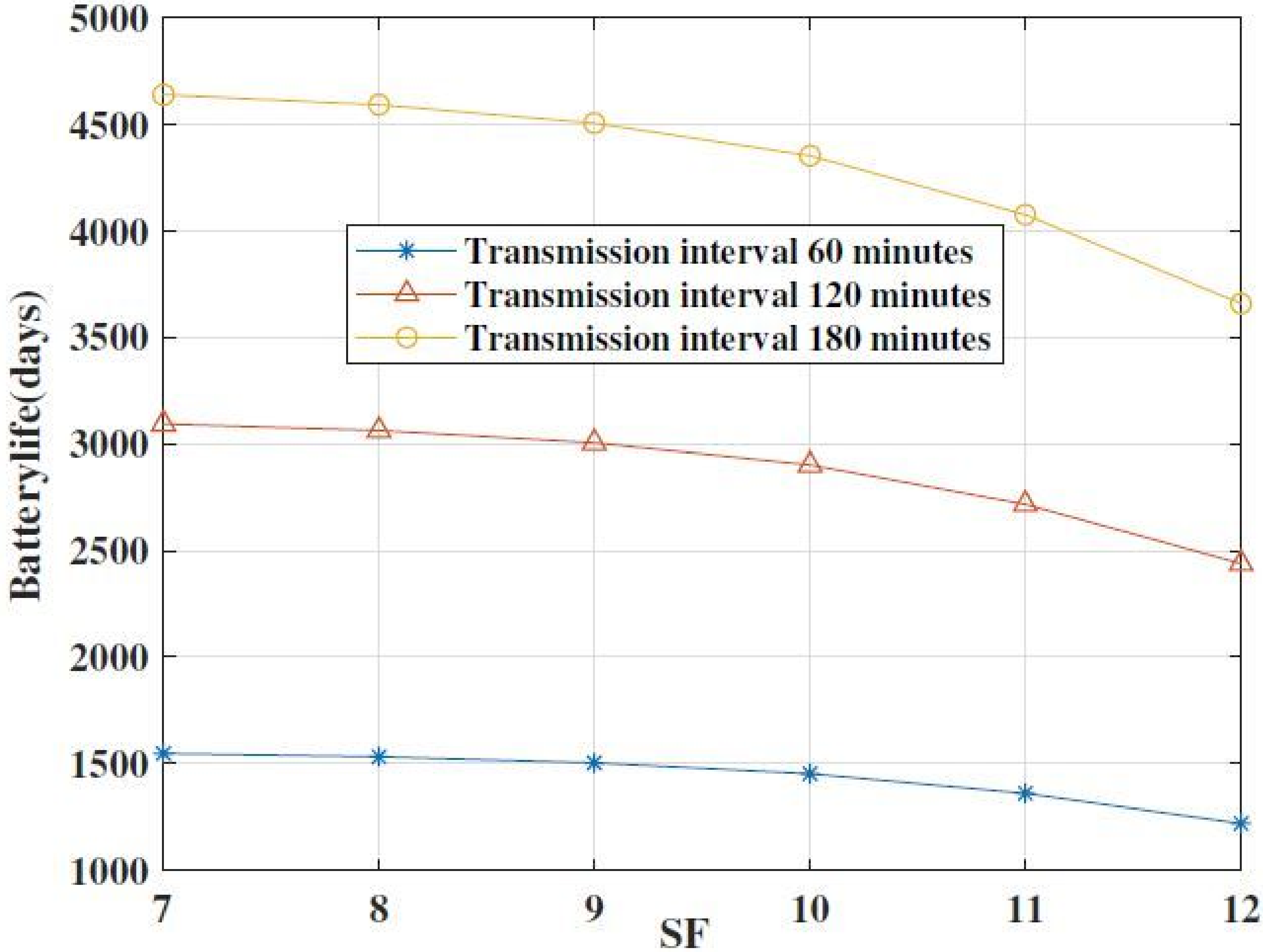

Figure 25

Battery Life time for different time

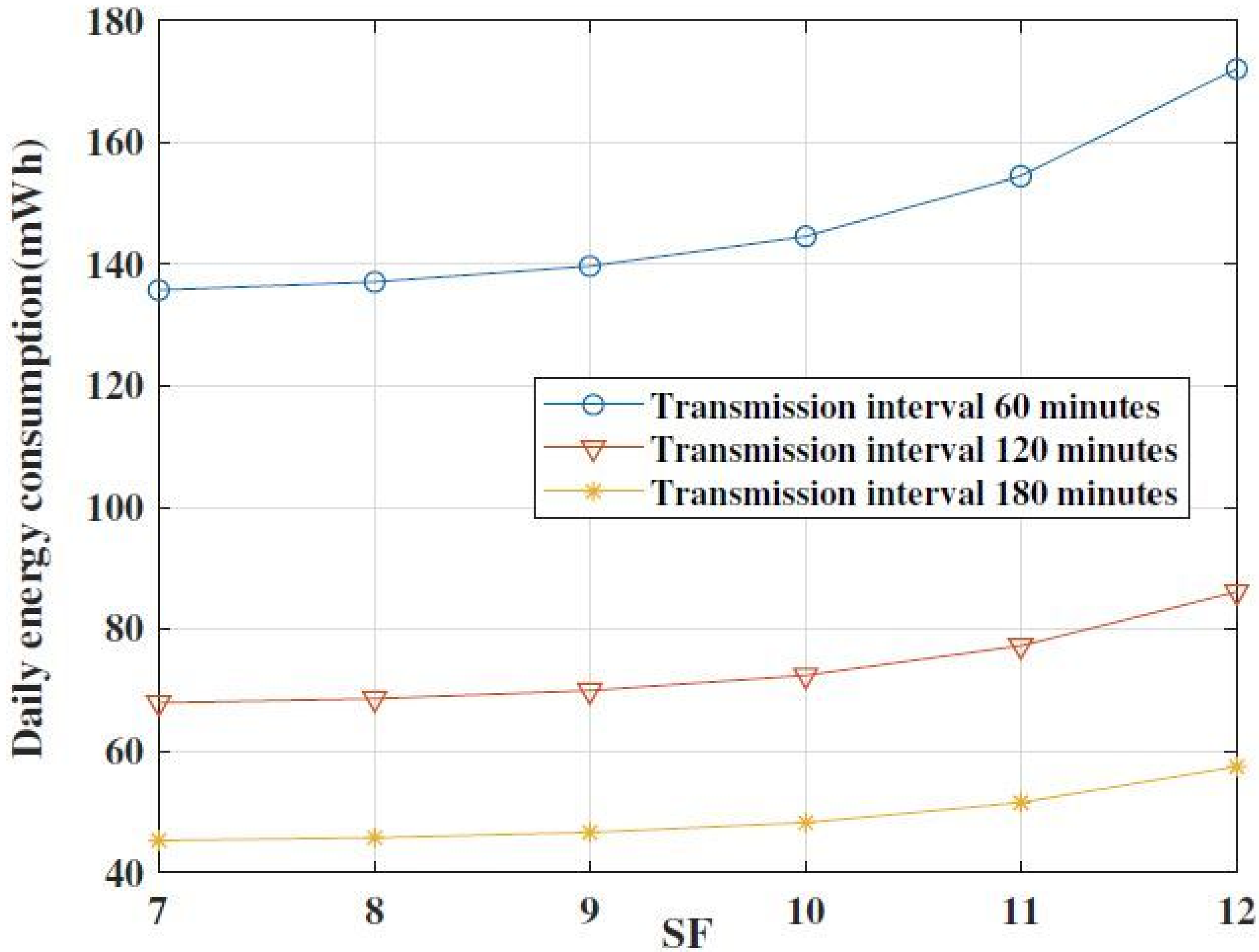

Figure 26

Daily energy consumption for different time

Supplementary Files

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