Analysis and Optimization of Low Power Wide Area IoT Network

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Abstract. LoRa (Long Range) is one of the latest Low power Wide Area Network (LPWAN) technology that has increased the number of IoT applications because of its extended battery life, low data rate and large coverage area. In this paper, we have investigated and analyzed the effects of different transmission parameters of LoRa on the estimated battery life of sensors. To extend the battery life of LoRa based sensors, optimal values of non-constrained parameters such as Spreading factor (SF), Coding rate (CR) and Bandwidth (BW) has been analyzed on the basis of Mean Square Error (MSE) Function. The potency of MSE is evaluated by the means of Artificial Neural Network using neural network fitting tool in MATLAB for simulations. In comparison to current prevalent lifetime of LoRa based node i.e. 10years, the optimization insights an increase in the battery life of nodes upto 19 years. Encapsulating these benefits of LoRaWAN, this technology has been proved as the propitious methods in different and wide applications of IoT.

Keywords: LoRa · Artificial Neural Network · Battery life

1 Introduction

The basic objective of IoT is to "connect the unconnected" [1]. IoT characterizes intelligence, complex system architecture, everything-as-a service, size, time and space considerations and hence anticipates duplex interaction among the devices like sensors, vehicles, home appliances, agricultural products, and other multidisciplinary IoT applications [2]. The three basic layers which jointly form topology of IoT are classified as the application layer, network layer, and perception layer. Bluetooth, ZigBee, Z-Wave, 2G/3G/4G/5G, LoRa, SigFox, Weightless, WAVIoT, and Wi-Fi HaLow - all are the technologies used in the network layer which interfaces the hardware and sensors of perception layer with the different applications in application layer like smart city, precision agriculture in suburban areas etc. [3, 4].

Many IoT infrastructure constitutes resource constrained (RC) devices. They are smaller in size, with less data handling capacity and power limitations. The battery lifetime of nodes in the networks are susceptible to premature failure because of more power consumption than other nodes due to workload variations, non-uniform set-up of communication and heterogeneous hardware requirements. Due to distributed-infrastructure, the nodes operation varies from one location to another and rapid multiplication of sensor

M. L. Gavrilova and C. J. K. Tan (Eds.): Trans. on Comput. Sci. XXXVIII, LNCS 12620, pp. 98–112, 2021.
https://doi.org/10.1007/978-3-662-63170-6_6

devices in modern applications results in increasing power consumption [5]. To control the energy, a number of technologies have been developed on the basis of coverage, lifetime and cost [6]. The technologies residing under this canopy are Ultra Narrow band by SigFox, NB-IoT, LoRa, RPMA by Ingenu, 3GPP: LTE-M, LTE-Cat 0 and Weightless-W, N and P. Classification of LPWAN technologies are based on operating frequencies as licensed and unlicensed. The main defiance faced by licensed bands service providers is the possibility of non-mobile service providers to in-take market share by offering IoT infrastructure and based devices without buying expensive spectrum. For resource constrained devices, unlicensed LPWAN technologies which have come into existence are LoRa, SigFox, Ingenu and Weightless. To transmit over long distance, LoRa is suitable as it works in the ISM band at 433, 868 or 915MHz with less energy consumption and low data rate. LoRaWAN protocol targets a trade between low power utilization and increased distance [7].

The present work is focused on LoRa, a modulation technique implemented on Chip Spread Spectrum (CSS) including physical layer specification. The outlined parameters of the LoRa radio which control the overall network performance are categorised as: Spreading Factor (SF), Bandwidth (BW), Coding Rate (CR) and the Carrier frequency. LoRa is capable to control different data rates via the coding rate, spread factor and bandwidth. And hence this helps in reducing the energy consumption, interference and error rates. However, due to increase in the utilization of LoRa in IoT applications, the availability of optimizing its performance parameters are still sparse. The optimized parameters helps in extending the lifetime of the LoRa based nodes. The optimization is performed using nftool which is based on Artificial Neural Network (ANN). The ambition of ANN is to define the Mean Square Error Function which evaluates the minimum error optimized value of the weights and performs the inter-linking among the neurons in different layer of system. The advantages of the ANN are- the ability to learn feed-forward mechanism, flexibility, fast implementation and low estimated error.The three important non-constrained parameters on which the optimization of battery life depends are: Spreading factor (SF), Bandwidth (BW) and Coding rate (CR). Lifetime denotes the number of days/year the node can perform operation without failure and delay [8]. These three prominent factors are the priority for optimization because most of the energy is consumed in data Communication. The main contributions of the paper are:

- Performance evaluation of a LoRa node by applying mathematical model comprising of diverse specifications of the LoRa network like SF, CR and BW.And also encases the effect of parameters on the battery life.
- Optimization of battery life of a LoRa node by considering all the combination of non-constrained parameters.
- Critical comparison of optimized and non-optimized value in respect of time on air, time cycle and energy cycle.

The rest of the work in the paper is categorised under the following headings: Related work in Sect. 2, followed by the study of LoRa and its parameters in Sect. 3. Section 4 includes the system model and the related equations. Section 5 underlines the optimization and its working principle. The outcomes are compiled in Sect. 6 and the conclusion is mentioned in Sect. 7.

2 Related Work

Several recent works has been focused on LoRa and its effect on the transmission configurations over IoT network. The parameters that have been the focal point in recent research are throughput, delay, coverage, energy, path loss and network density. The earlier proposed work derives the intricate SF, bandwidth and transmission power to increase the throughput by manyfold. Many researches have been undertaken regarding the reduction of energy consumption of different classes of nodes by controlling the transmission power [9]. Table 1 summarizes some of the previous work based on performance and computational analysis of nodes, outlined parameters and resource management.

Table 1. Comparison of related works

References	Performance metrics	Highlighted features	Results accomplished
[10]	Power and bandwidth	Proposed a mathematical formula in terms of power and band usage	Throughput increases by 238.8%
[11]	Energy	Accounts the modeling of the Class A sensor node units	Minimization of energy consumption during acknowledgement transmission
[12]	Throughput	Optimizes a global network configuration to maximize throughput	Increase in throughput by 147% in the network of 200 IoT nodes
[13]	Energy and packet loss	Highlights the trade-off between SF and transmission power	Reduction in energy consumption from 30J to 15J by bandit algorithm
[14]	Network density	Behavioral analysis of LoRa networks using message replication	In low density networks replication is useful
[15]	Path Loss	Utilized LoRa to maximize coverage in dense urban area	Gateways and channels are analyzed for multipoint-to-point communications
[16]	Throughput	Increased time-on-air is compensated by the reducing the interference	Throughput increases by 30%
[17]	Energy	Optimizes SF to increase the PRP for the average energy consumption	Current consumption reduces to 63mAh with increase in PRP performance
In proposed work	Battery life	Analyzing the effect of SF, CR, TOA and BW on Battery life and optimizing these parameters to achieve increased battery life	The battery of the node can last upto approx. **19 years** as compared to presently defined lifetime i.e. 10 years

Although, the above described related works have shown a detailed analysis of LoRa and its parameters, but none of them has made an attempt to optimize all the outlined non-constrained parameters to evaluate the extended lifetime of the nodes. Exceptionally, in the paper [17], energy is minimized by optimizing the SF to increase the packet reception rate but it does not define the lifetime of individual nodes that is dependent on the low duty cycle, SF and TOA. It is necessary to select a good transmission parameter configuration so that the energy consumption and performance network is balanced.

The proposed work is different from the previous studies in a way that it focuses on the optimization of various parameters through mean square error based approach. It is aimed to achieve the pre-eminent set of non-constrained parameters that will prioritize the battery life.

3 LoRa and LoRaWAN

The LoRa Alliance is an association formed in 2015. It standardizes the LPWAN with the different specifications of LoRaWAN. It has developed compliance program and a certification that ensures interoperability. The basis of LoRa is chirp spread spectrum modulation technique and it manages the trade-off between low data rate and increased distance. The parameters affecting the LoRaWAN end devices operation and power consumption are assimilated by the performance of Physical layer and Medium Access Control (MAC) layer. The physical layer is designated to assign the data rate, spreading factor, bandwidth and transmission power. The MAC layer illustrates the LoRaWAN battery life optimization [18]. The performance requirements for MAC layer are throughput, stability and energy efficiency. To optimize end applications, LoRaWAN utilizes various device classes. The device class deals with network downlink latency versus battery lifetime.

The physical parameters of a LoRa device required to tune its performance are Spreading Factor (SF), Coding rate (CR), Transmission power (TP) and Bandwidth (BW). The SF decides the carrier of data on specific number of chirps required. It ranges from 7–12. Higher the value of SF, higher will be the Signal to Noise Ratio (SNR). The other parameter, that is, CR adjusts the ratio of bits transmitted to the actual information bits. The coding rate is defined as $4/(4 + CR)$. Here the value of CR can be set as 1, 2, 3 or 4. The value of $CR = 4/5$ indicates that, one bit of correction code is added with every four bits of data. On the other hand, the value of $CR = 4/8$ refers that four correction bits are added with four bits of data. Although, the higher value of CR provides protection, it also shoots up the time on air (TOA). The TP is the power required for transmission of a specific data packet. It ranges from 2dBm to 20dBm. Lastly, the range of frequencies is specified by bandwidth. LoRa operates at 125 kHz, 250 kHz or 500 kHz. With the increase in BW, data rate increases and simultaneously sensitivity decreases due to short TOA. The computation of TOA of LoRa transmission is done according to the combination of several radio parameters: SF, BW, and CR and payload size [19]. These parameters affects the energy consumption notably and the variations can be clearly identified in terms of time cycle (T_{cycle}) and energy cycle (E_{cycle}).

The various applications incorporating LoRaWAN technology in the present scenario includes Water and gas leakage detection, Smart building security, Inspection of safety, Space optimization and many more. Concentrating on health services, the WBAN is made of several biosensors which is either implanted or deployed on the body to measure medical parameters like arterial pressure, body temperature and EEG Signal [20]. Secondly, WBAN is also prominent solution for military actions such as safeguarding. But the depletion of battery life due to continuous use of the optimal sensors leads to a rapid minimization the lifetime. The features of the applications are utilized in day-to-day life for safe and secure living, making long battery life and energy efficiency as the key aspects to meet the applications requirement. The two key aspects of the nodes and their inter-dependence on the radio parameters are analyzed by the mathematical equations as described in the next section.

4 System Model

The useful combinations of parameters need to be selected for evaluating the important details of energy consumption of the end nodes. The energy consumption of single node depends on its active and sleep state. LoRa promises that the long life of a node is only possible through careful selection of parameter configuration and duty cycle. The ratio of time during which device is in active state to the total time (i.e. active state and sleep state) is known as duty cycle. When the sleep state increases, the duty cycle decreases resulting in the reduction of power consumption. To calculate the lifetime, the radio parameters that are utilized are pointed below-

The equivalent bit rate (R_b) in LoRa [21] is given in terms of

$$R_b = SF * \left(\frac{4}{4 + CR}\right) * \left(\frac{1}{T_s}\right) \tag{1}$$

Here, T_s represents the symbol time. The TOA defines the amount of time each device takes for transmission of total packets and is calculated by the physical layer payload size. In LoRa, the payload length varies between 51 bytes-222 bytes.

$$T_{payload} = \left(n_{payload}\right)(T_s) \tag{2}$$

Where, $T_{payload}$ is the TOA of payload (ms) and $n_{payload}$ is the payload length. Similarly, LoRa physical packet contains preamble of 2 symbols of synchronized word and 2.25 symbols of SFD. The preamble duration ($T_{preamble}$) can be calculated using Eq. (3).

$$T_{preamble} = (N_{preamble} + 4.25) * T_s \tag{3}$$

Here, $T_{preamble}$ denotes the preamble duration in (ms), $N_{preamble}$ represents the length of preamble and T_s is the symbol time in (ms). TOA is the transmission of total message bits i.e. a combination of payload duration and preamble duration [20] and is computed with the formula-

$$T_{packet} = TOA = T_{payload} + T_{preamble} \tag{4}$$

By substituting the value of Eq. (2) and (3) in Eq. (4)

$$TOA = [n_{payload} + N_{preamble} + 4.25] * T_s \tag{5}$$

The modified form of TOA on the basis of bit rate [20] can be defined as-

$$TOA = \frac{\left[n_{payload} + N_{preamble} + 4.25\right] * SF * CR}{R_b} \tag{6}$$

The duration for which the device is in silent state T_{off} [22], is calculated by

$$T_{off} = \frac{TOA}{Duty\ Cycle} - (TOA) \tag{7}$$

Here, the duty cycle defines the ratio of active period to total time period of a node. The relation between the T_{off} and TOA is represented in form of T_{cycle} as

$$T_{cycle} = T_{off} + TOA \tag{8}$$

Since duty cycle is the duration of time a node is transmitting, the cycle duration T_{cycle} indicates a fraction of time for which the node is allowed to transmit. Here TOA represents the transmission duration of a packet. The total time taken to complete one cycle of transmission and reception of message bits is given by the formula-

$$T_{cycle} = 100 * \left(\frac{TOA}{Duty\ Cycle} \right) \tag{9}$$

The parameter T_{cycle} is the time duration of a single transmission cycle. Energy parameters 'Energy consumed' and 'Energy cycle' each indicates the energy contained in a battery and energy expended for every transmission. The lifetime of battery in Eq. (9) is assumed as a perfect battery with no degradation [22].

$$\text{Lifetime} = \mathrm{T_{cycle}} * \left(\frac{Energy\ consumed}{Energy\ cycle} \right) \tag{10}$$

5 Optimization Using ANN

Neural network fitting tool (nftool) of MATLAB is used to carry out optimization. It has been discovered in (10) that lifetime of the node depends upon the various parameters like time on air, bandwidth, payload length, spreading factor, duty cycle, coding rate, preamble length, energy consumed and symbol time. These parameters have been calculated with the help of LoRa calculator. Spreading factor, coding rate, bandwidth and duty cycle are termed as free parameters or non-constrained parameters because they are non-linear in nature. The optimization has been performed utilizing the free parameters.

In ANN, the network design is illustrated in Fig. 1. The network design is made up of three layers and the three layers are Input layer, Hidden layers and Output layer. The first layer, that is, the input layer sends the input variables to the hidden layer. Hidden layer lies in the middle of input and the output layer. It contains artificial neurons that take a set of weighted inputs. The activation function produces the output. The output layer is responsible for generating output received from hidden layer. The number of neurons in hidden layer has to be chosen carefully to avoid issues like under fitting, over fitting and increase in training time of the network. A set of input is fed which leads to specific output. The comparison is made between the output and the input target, until the network output matches with the target. The goal of ANN is to calculate the Mean Square Function (MSE). To decrease the error of the increased data sample, the average of distribution is taken. For proposed ANN model, spreading factor, bandwidth, coding rate, duty cycle and energy consumed have been used as input parameters and battery life is used as output parameter.

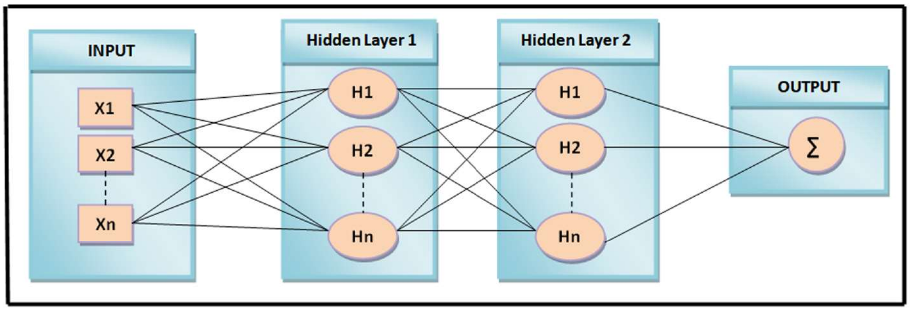

Fig. 1. ANN based "nftool"

A total of 108 samples in the data set have been created to find the optimized value. The hidden layer contains 10 neurons. The created dataset has been bifurcated into training set and testing set. These sets have been further selected for testing and validation purposes. The training set uses 70% of the data and remaining data is used as test set. Neural network is trained to perform the specific function by calibrating the value of weights (connections) between the elements. The performance evaluation of the ANN is represented and analyzed by four different plots- Regression plot, performance plot, training state plot and error histogram graph. The next section portrays the performance analysis of the proposed model with the help of simulation results.

6 Results and Discussions

The effectiveness and the inter-dependence of the LoRa transmission parameters is numerically simulated with the help of LoRa Calculator Tool developed by Semtech. This software is based on LoRa modem and allows quick evaluation of several LoRa configurations by simplifying design decisions (Table 2).

Table 2. Simulation parameters

Parameters	Value
Carrier frequency	865 MHz
Spreading factor	7 to 12
Bandwidth	125 kHz, 250 kHz, 500 kHz
Coding rate	4/8, 4/7 and 4/6
Payload length	8 bytes
Programmable preamble	8 symbols
Total Preamble length	10.25 symbols
Transmission power	17 dBm
Battery capacity	1000 mAh

It is known that LoRa sensors operate for many years without a constant power supply. The energy consumption of different states depends on selected SF and BW. The goal of our objective is to analyze the effect of variables in the considered scenario for extended battery evaluation of the system along with energy efficiency. The lifetime factors of the nodes are TOA, T_{cycle} and $E_{cycle.}$ The various effects of the transmission parameters on the lifetime factors has been analyzed graphically and the observed results are utilized as the base parameters in the optimization.

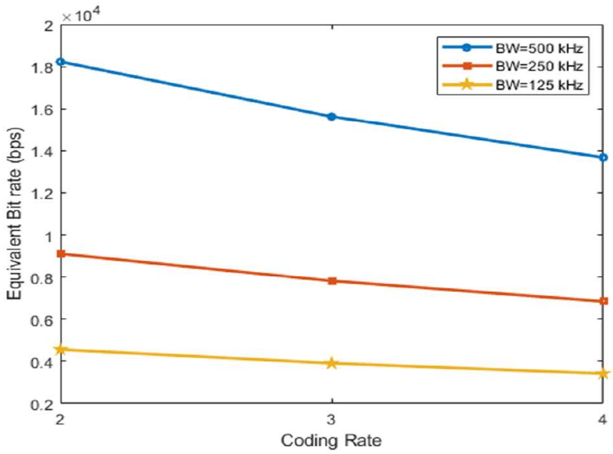

Fig. 2. Effect of coding rate and bit rate considering variable bandwidth

Figure 2 shows the effect of different CR and bandwidth on bit rate. It is analyzed that at a particular BW, when the CR increases then equivalent bit rate decreases due to increase in TOA. Secondly, as the BW increases i.e. more data is received at the same time, the bit rate also escalates. For the present IoT applications, LoRa can be fruitful because as the bit rate increases rapidly with increase in BW, at a particular SF, it results in high speed of data transmission with less number of redundant message bits.

Similarly, Fig. 3 presents the effect of SF and CR on TOA. It is concluded that as the SF increases at a specific CR, the value of TOA also increases because the increase in number of chips in a symbol leads to more time in processing gain at receiver side. This reduces the Battery Life of the devices and increases the energy consumption. It is required to examine that while sending a LoRaWAN message, most of the time is

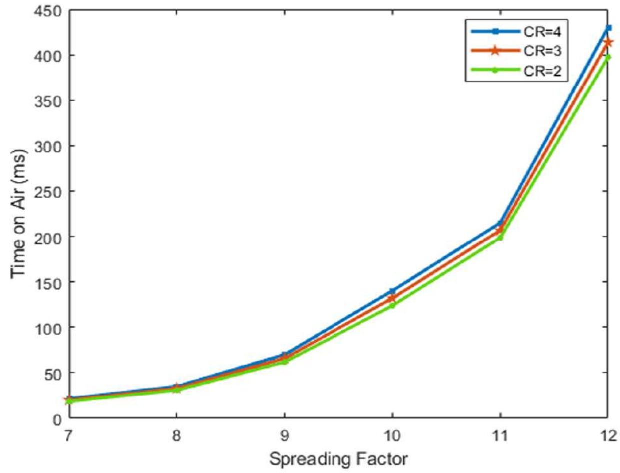

Fig. 3. Effect of Spreading factor and coding rate on time on air

spent on waiting for receive windows acknowledgment. Secondly, with the increase in CR, the TOA increases. In LoRa, the higher SF is not suitable for long life devices. It is generalized that SF = 7 is acceptable value for many smart applications because the lowest transmission time is guaranteed by SF 7. It minimizes the interference.

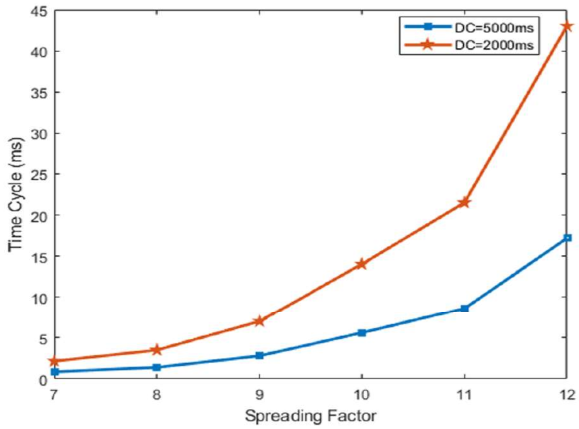

Fig. 4. Effect of spreading factor and duty cycle on time cycle

The term 'time cycle' is directly proportional to the TOA and inversely proportional to the duty cycle. In LoRa Calculator, the duty cycle is calculated in terms of 'ms'. Figure 4 depicts the effect of duty cycle and CR on time cycle. It is noticeable that as the spreading factor increases, time cycle increases hence shooting up the energy consumption. Also, as the duty cycle decreases at a particular SF, the time cycle increases indicating that the device is in OFF state when not required. The energy cycle represents the total energy consumption during transmission and reception of the message.

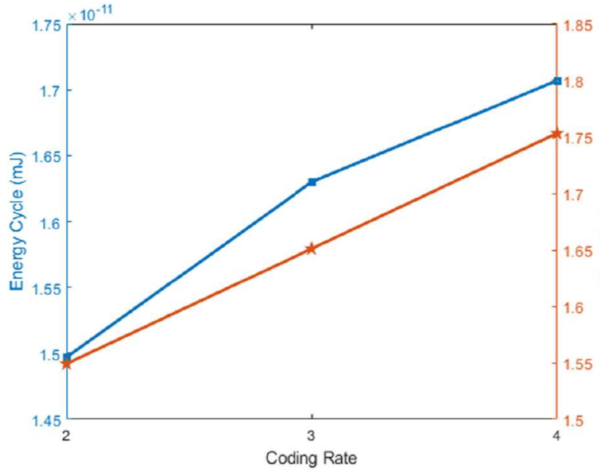

Fig. 5. Effect of coding rate on time cycle and energy cycle

On the other hand, Fig. 5 presents the effect of different CR on time cycle and energy cycle. It is noticed that as the coding rate increases, the energy cycle and time cycle also increases. This means that the increase in number of redundant bits increases the TOA and hence both the cycle also increases.

As discussed earlier, the data set containing 108 samples has been created by taking various combinations of non-constrained parameters of LoRa. The impact of all the parameters is analyzed graphically. It has been discovered that with the minimum SF and higher bandwidth, the lifetime of the node increases. Keeping this in mind, ANN has been implemented for optimization, considering SF as the base parameter associated with the bandwidth. Figure 6 represents the regression curve fit of input and output dataset. Regression plot tracks the targets for training, testing and validation with respect to output. The value of R should be less than 1.To evaluate the optimal extended battery life, an optimized value of free-parameters is obtained using the mean squared error plot. Figure 7 depicts the minimum error that has been observed using the mean square error graph. It highlights the coordinates of the optimized value. The x-coordinate represents the input sample number and corresponding to it the y-coordinate shows the minimum error value.

With the help of coordinates of the minimum error, the optimized value of all the input parameters and the output parameter has been analyzed and listed in Table 3. The IoT applications using LoRa based sensor is battery constraint. It is not feasible to

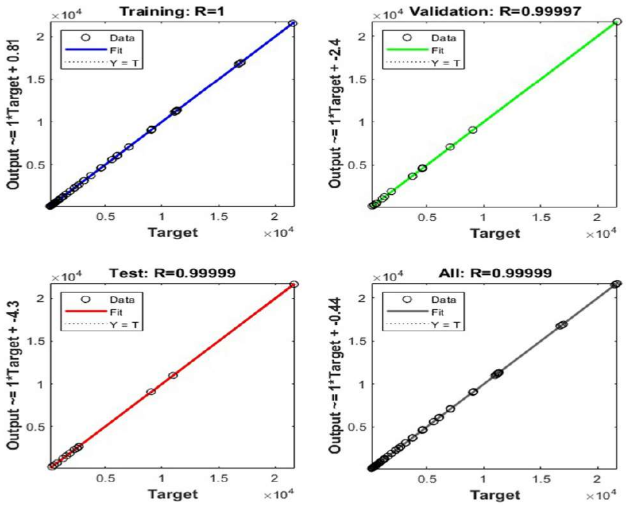

Fig. 6. Regression and error histogram plot of nftool for training and testing of network

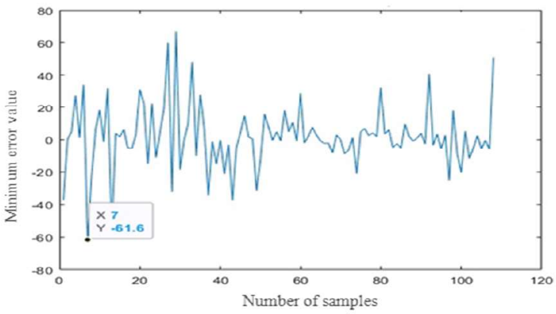

Fig. 7. Mean squared error plot

replace or recharge the battery frequently. Therefore, power and energy optimization is required to make an energy efficient network.

Table 3. Optimized value of transmission parameters

Parameters	Optimized value
Spreading factor (SF)	7
Coding Rate (CR)	4/8
Bandwidth (BW)	250 kHz
Duty Cycle (DC)	2000 ms

It has been analyzed that the maximum battery life to be accommodated with optimized parameters is **7051.23 days (approximately 19 years)**. The resultant optimized value of the parameters of LoRa are- SF = 7, BW = 250 kHz, CR = 4/8 and duty cycle = 2000 ms. All of these diverse parameters play an important role in analyzing the lifetime of the nodes as they determine the time duration of a packet and the amount of energy consumed during the transmission. It is also evident that the energy cycle of the optimized value is less than the average value of non-optimized data samples. Hence, the low energy consumption of the optimized value has turned out to be beneficial and efficient in future for various IoT applications.

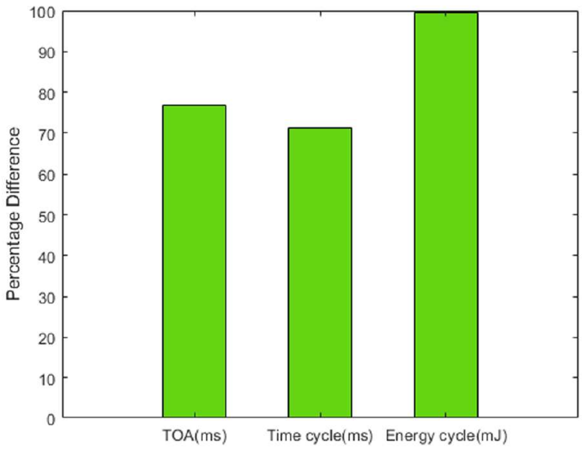

Fig. 8. Percentage difference between optimized and non-optimized value

Figure 8 presents the percentage difference between the optimized and non-optimized values. The percentage difference value of TOA, T_{cycle} and E_{cycle} has been recorded as 76.75%, 71.23 and 99.56% respectively. Correspondingly, in Fig. 9 the comparison of the optimized and non-optimized values has been represented graphically in terms of lifetime factors. The results show that the evaluated optimized value of transmission parameters has proved to be better than conventional values with minimum time on air and minimum energy utilization. This also demonstrates that optimization method proposed on the LoRa transmission parameters is efficient in relation to the other optimization methods presented.

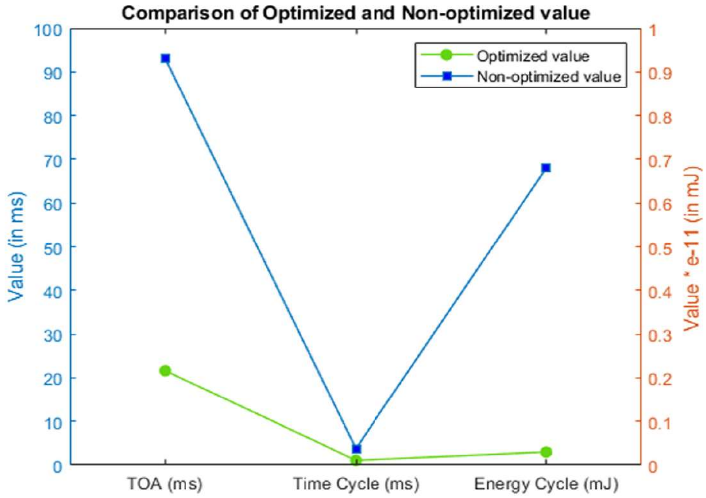

Fig. 9. Comparison of optimized and non-optimized value

7 Conclusion

Based on the evaluation of LoRa technology, the proposed research enlists the effects of LoRaWAN features on the device performance. The performance has been evaluated graphically and the significance of each diverse parameter has been observed. Results highlight the percentage difference between the optimized and non-optimized values as 76.75%, 71.23% and 99.56% for TOA, T_{cycle} and E_{cycle} respectively. In addition, the optimization has been achieved with the help of ANN and it was concluded that the estimated battery life can be extended upto approximately 19 years. The real time IoT applications require extended battery life and minimal power consumption. Since IoT deployment acknowledges "heterogeneity", a large number of devices are needed that can increase the scalability, stability and reliability of the system. Therefore, to implement innovative energy efficient IoT applications, an energy efficient management system has become an essential concept to be considered while designing the system.

The future scope lies in the field of its application where these devices can play their role for more number of years and its sensing capability will be highly intelligent in architecture. In recent scenario, sensors are required that will be easily installed in human for health monitoring, military applications or environment activity monitoring of large geographical area. All these applications require low power consumption and advanced reliable technology. Also, different optimization techniques and their computational cost can be compared.

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