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Analysis and optimization of downlink energy in NB-IoT

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ABSTRACT

The efficient and simpler version of Internet of things (IoT) is Narrowband Internet of Things (NB-IoT). It is a low power wide area network (LPWAN) technology standardized by Third Generation Partnership Project (3GPP) and is mainly used for LPWA applications. The deployment of NB-IoT is easy and it utilizes low power. To extend the possibilities of NB-IoT in terms of coverage, traffic and power,efficient energy consumption has become a concern. In this paper, the NB-IoT model has been analysed with respect to the reception of downlink (DL) packets. Energy optimization of downlink packet has been done with the help of particle swarm optimization (PSO). By optimizing the non-constraint parameters of NB-IoT,84.98% and 61.07% decrease in energy consumption has been observed. Overall, average energy efficiency of the system has been increased. The non-optimized and optimized NB-IoT systems have been critically compared.

1. Introduction

The Internet of Things (IoT) defines the interconnectivity of devices from every corner of the world. IoTis narrowing the distance between the actual world and the advanced world, thereby making exceptional automation in every industry. Complex tasks requiring computing, intelligence and networking are fulfilled by the different type of IoT devices such as sensors, processors, transceivers and actuators. IoT does not aggregate single technology, rather it is an integration of various other technologies [1]. The IoT advancements in sensing, processing and data communication have piqued the researcher's interest towards the major challenges of IoT.The major challenges are scalability, reliability, energy efficiency, long-range communication and security. Various IoT applications require energy-efficient nodes which are to be deployed on scalable networks. Technologies such as Bluetooth and ZigBee are utilized for short-range and low-data rate environment. Wireless Local Area Networks (WLANs) are used for high speed data transmission in local environment [2]. Thus, Low Power Wide Area Network(LPWAN) has evolved as a wireless technology that has driven major challenges of IoT applications.Long-range transmission, low-data rate and low energy consumption are significant advantages of LPWAN technologies.

Numerous LPWAN technologies have been categorized in the licensed and unlicensed band.Among these technologies Sigfox, Long-range (LoRa), and Narrow-band IoT (NB-IoT) are the recent driving advances that include numerous specialized contrasts [4]. SigFox operates in the unlicensed band and employs Ultra-Narrow band technology with maximum data rate of 100 bps [3]. LoRa is a wide area network technology based on LoRaWAN standard protocol. It also operates in the unlicensed band with data rate of 200kbps. On the other hand, NB-IoT operates in the licensed band with data rate of 100kbps. NB-IoT has smaller latency time of 10 s and better Quality of Service (QoS) as compared to LoRa [4]. For large scale IoT deployment, energy efficient devices are needed to achieve longer lifetime. The massive connectivity of devices is being supported by NB-IoT with an added advantage of spectrum reuse. It also supports multiple types of resource units and determined number of repetitions for the transmission of data in order to enhance the reliability of communication [5]. Hence, NB-IoT becomes the prominent solution for major IoT challenges. For both uplink (UL) and downlink (DL) operations, the user equipment in NB-IoT supportsthe bandwidth of 180 KHz. Increase in repetitions and power spectral density (PSD) also increases the coverage and impacts the energy consumption. The radio transmission consumes a major portion of energy.The energy consumed in sending the data to the network and receiving the data from the network is more as compared to the energy consumed in processing the data. Thus, optimization of energy has become a hot topic of research because the energy efficient systems are gaining importance day by day [6].

In this paper, the particle swarm optimization (PSO) technique is used to optimize the energy consumed by the downlink reception of packets for NB-IoT. Also, the power consumed by user equipment (UE) due to reception of packet are analyzed by performing the mathematical modelling. The proposed PSO algorithm optimizes the parameters such

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as power consumption, number of sub-frames and length of MAC header. PSO reduces the overall energy required by UE thereby simultaneously increasing the average energy efficiency of the system.The major contributions of this paper are as follows-

- Mathematical modelling of NB-IoT comprising of diverse parameters such as repetitions, number of sub-frames, power consumption, number of segments and reception time of downlink packets has been analysed. It further encases the effect of these diverse parameters on the energy consumption.
- Considering the combination of non-constrained parameters, energy optimization of downlink packet in NB-IoT, has been evaluated using PSO algorithm.
- Critical comparison of optimized and non-optimized value of energy consumption in respect of number of repetitions, transport block size and number of segments.

This paper has been organized in the following sections: Section 2 discusses the related work. The brief overview of NB-IoT technology is mentioned in Section 3. The proposed system model has been discussed in Section 4, followed by Energy optimization using PSO in Section 5. Section 6 holds the simulation results. The conclusion is discussed in Section 7.

2. Related work

Specific requirements of IoT such as low data rate, low energy consumption and long range have created an urge towards the considerable research and development. The research area that has caught the attraction in this field is LPWAN. In the present scenario, the two most popular LPWAN technologies are Long-range (LoRa) and NB-IoT in unlicensed and licensed band, respectively.The other existing IoT technologies are also used as per different IoT requirements. Table 1 shows the comparative analysis of different LPWAN technologies with NB-IoT. It also compares the recent research work considering the significant factors of NB-IoT.

In [7], the battery life of LoRaWAN is optimized using Artificial neural network (ANN). The comparative analysis of major LPWAN technologies operating on unlicensed band, on the basis of coverage, latency and packet error rate has been discussed in detail in [8]. Similarly, in [9], the comparative analysis of NB-IoT and LTE, operating in licensed band has been carried out in terms of energy consumption, range and latency. Considering the present challenges of IoT, increasing energy efficiency has become one of the major concern and therefore in [10] and [11], diverse characteristic of NB-IoT is analyzed and it is concluded that the relative error of 21% is achieved in terms of energy and lifetime.

Focusing on the need of high energy efficiency, this paper presents the optimization of downlink energy consumption in NB-IoT. As NB-IoT is capable of providing a wide range of coverage, the devices need to run for longer periods.This makes the energy consumption a critical issue and therefore there is a need to reduce the energy consumption. The computational efficiency and easy implementation of PSO motivates us to implement this algorithm for energy optimization in this paper.

3. Proposed system model

The crux of NB-IoT is its increased battery life due to its low energy consumption. Findings have validated that the NB-IoT model incorporating uplink, downlink, scheduling, free-parameters optimization, modulation and coding schemes have incredibly helped in reducing the energy consumption.In the physical layer, NB-IoT consists of three downlink channels: Narrowband Physical Downlink Control Channel (NPDCCH), Narrowband Physical Broadcast Channel (NPBCH), Narrowband Physical Downlink Shared Channel (NPDSCH) [12]. The MAC and network layer controls the delays, power consumption and battery life of IoT devices. The NPDSCH is responsible for data transmission and is utilized to transmit information blocks and the data to the users.It has been already recognized that the maximum power consumption in IoT applications occurs during data transmission.Thus, to minimize the energy consumption, NB-IoT adopts Power Saving Mode (PSM) and Extended Discontinuous Reception (eDRX) [13]. PSM is the state which helps in extending the battery life of the NB-IoT devices and the UE does not monitor any information or paging. To analyze the energy consumption of UE at different phases of transmission and reception, the energy consumption model has been defined in Fig. 1. Here, the UE and eNodeB exchange the information using different channels.

Fig. 1 depicts five different UE energy levels that has been analysed and mathematically modelled in this section. Downlink Control Information (DCI) mostly handles the scheduling of NPDSCH [14]. The UE initially decodes the received DCI to acknowledge the NPDSCH data. The energy consumption during downlink (DL) has been considered to perform a detailed analysis of DL energy consumption of NB-IoT device. Energy consumption depends directly on the product of power consumed and the transmission time. The symbols and its description, used for deriving the objective function in the proposed work has been listed in Table 2 below.

The total energy consumed during the reception of DL packet(y) includes the energies consumed during reception, transmission gap and downlink segment and it has been given in Eq. (1) [15]:

$$E_{rx}(y) = P_{RX}.T_{RXDL}(y) + P_i.T^{DL}_{Gap}(y) + \quad E_{seg}(y) \tag{1}$$

Here,P_{RX} is the power consumed by the UE to receive a DL packet from the network and P_i is the power consumed when UE is in the standby mode.$T^{DL}_{Gap}(y)$ is the time when UE remains active and waits for the downlink transmission gap to end.For the calculation of energy consumption, the time required to receive a DL packet, $T_{RXDL}(y)$ is

Table 1
Comparative study of existing LPWAN technologies and NB-IoT with respect to various performance metrics.

References	Utilized Technology	Approach	Analyzed Performance Metrics				
			Coverage	Latency	Energyconsumption	Battery Lifetime	Energy Optimization
[7]	• LoRa	Evaluated the significance of LoRa parameters and optimized the battery life.		✔		✔	✔
[8]	• LoRa • NB-IoT • SigFox	Evaluated the performances of defined technologies.	✔	✔			
[9]	• NB-IoT • LTE-M	Analyzed the performance of indoor and outdoor devices.	✔	✔	✔		
[10]	• NB-IoT	Analyzed the model performance in terms of battery life.		✔		✔	
[11]	• NB-IoT	Observed the critical characteristic of NB-IoT		✔	✔		
Proposed Work	• NB-IoT	Performed Mathematical modelling to calculate the energy required to receive a downlink packet in NB-IoT			✔	✔	✔

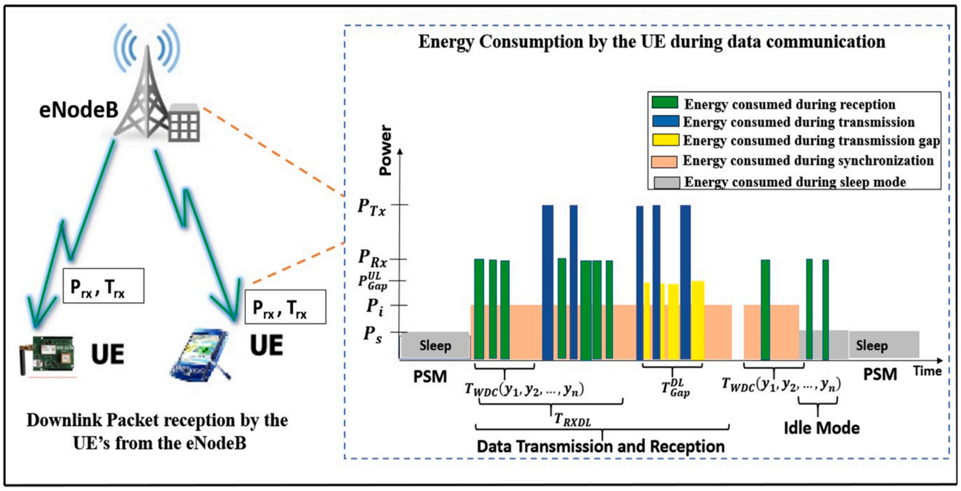

Fig. 1. Energy Consumption by the User Equipment (UE) at different states of NB-IoT.

Table 2
The mathematical symbols notations.

Serial Number	Symbol	Description
1	P_{Tx}	Transmission power
2	P_{Rx}	Reception power
3	P^{UL}_{Gap}	Transmission gap power
4	P_i	Power consumed during synchronization
5	T_{RXDL}	Reception time of downlink packet
6	T_{RX}	Total reception time
7	T^{DL}_{Gap}	Time UE remains in active state
8	E_{seg}	Energy of downlink packet segment
9	E_{rx}	Reception Energy
10	N_{seg}	Number of segments
11	$T_{WDC}(y_1, y_2, \ldots, y_n)$	Wait time period
12	T_{wDC2DS}	Downlink shared channel transmission time
13	N_{REP}	Number of repetitions
14	N_{SF}	Number of sub-frames
15	$TBS(MCS, N_{RU})$	Transport block size depending on modulation coding schemes and number of resource units.
16	H_{RLCMAC}	Length of MAC header.

needed.$E_{seg}(y)$ is the energy consumption due to downlink control information's between downlink packet segment and is given in Eq. (2) [16]-

$$E_{seg}(y) = \left(N_{seg}(y) - 1\right).\left(P_{RX}.T_{RX}(dci) + P_i.\left(T_{WDC}(y_1, y_2, \ldots, y_n) + T_{wDC2DS}\right)\right) \tag{2}$$

where $N_{seg}(y)$ is the number of segments and T_{wDC2DS} is the commencement of NPDSCH transmission after the termination of linked DCI. To calculate the energy consumption, the reception time for the DCI,$T_{RX}(dci)$ is required. In order to save energy after an interval of discontinuous narrowband physical downlink control channel, the UE moves to power saving state. The power saving state occurs periodically. The time period, $T_{WDC}(y_1, y_2, \ldots, y_n)$ required till the arrival of next power saving state is the waiting period [6].

In accordance with the NB-IoT standard, the transmission resource units of a UE can be associated with the number of repetitions. The NB-IoT extends the coverage of base station by utilizing the number of repetitions. The number of repetitions can be given using Eq. (3) [17]-

$$N_{REP} = 2^l \tag{3}$$

where $l \in \{0, 1, 2, 3, 4, 5, 6, 7\}$.

The N_{REP} is adopted by NB-IoT to enhance the coverage of IoT applications in the areas such as basements and deep indoor environment using the l repetition values. Increasing the coverage will also impact the energy utilization. Thus, N_{REP} has been considered as a major parameter in this current work to analyze its effect on the energy consumption. The downlink reception time of a packet is given using Eq. (3) [18]-

$$T_{RX}(y) = \left(\frac{10}{7}\right).N_{REP}.N_{SF}.N_{seg}(y) \tag{4}$$

where N_{REP}represents the number of repetitions and is defined in Eq. (3), N_{SF} is the number of sub frames and $N_{seg}(y)$ is the number of segments. NB-IoT consists of 10 sub-frames each with the duration of 0.5 ms. Sub-frames enable data synchronization which helps the network to manage data correctly. Data synchronization also consumes energy during transmission. Thus, N_{SF} also plays an important role in this current work. Using Eq. (3) in (4), the reception time of DL packet in terms of number of repetitions, sub-frames and segments has been given in equation below [19]-

$$T_{RXDL}(y) = 2^l.\left(\frac{10}{7}\right).N_{SF}.N_{seg}(y) \tag{5}$$

Similarly, analyzing the duration of DL gap during transmission has been given in (6) and (7) indicating the interdependency of sub-frames and number of segments[20]-

$$T^{DL}_{Gap}(y) = \frac{2^l.N_{SF}.N_{seg}(y)}{3} \tag{6}$$

$$N_{seg}(y) = \left\lceil \frac{L_y}{TBS(MCS, N_{RU}) - H_{RLCMAC}} \right\rceil \tag{7}$$

where L_y is the length of DL packet in bits, TBS is the transport block size for NPDSCH depending on modulation coding scheme (MCS) and number of resource units (N_{RU}), and H_{RLCMAC} is the length of RLC/MAC header. The MAC header includes the field of device identification and error detection. The length of header can vary, and it helps in synchronization with the network. Hence, the length of MAC header has been considered for optimization in the proposed work. TBS increases the number of bits to be sent per transmission in order to minimize the power consumption and transmission time for large data. To limit the energy utilization, the UE goes to power saving stateperiodically. Considering these features of NB-IoT, the main objective of efficient energyconsumption can be expressed by energy optimization. In next section, the PSO algorithm and energy optimization using has been discussed briefly.

4. Energy optimization using PSO

Real-time IoT applications demands energy conservation and thus energy optimization becomes a necessity in various real-life applications. Particle Swarm Optimization (PSO)algorithm generates high-quality solution in limited time, making it extensively employed for energy optimization. To compute the optimal solution, PSO improves the candidate solution by approximation and non-deterministic technique. The main characteristics of PSO are simple algorithm, easy to implement, robustness and high computational efficiency. Every particle denotes the potential solution and supersedes the best position solution. There also exists the particle with greatest fitness which is known as global best of the swarm. Every particle modifies the best position and global best solution according to the current position, current velocity, distance between best and current position and distance between global best and current position [21].

The control parameters of NB-IoT for detailed analysis of DL energy consumption in NB-IoT device is observed using the proposed objective function given below-

$$E_{rx}(y) = P_{RX}.T_{RXdl}(y) + P_i.T^{DL}_{Gap}(y) + \left(N_{seg}(y) - 1\right).(P_{RX}.T_{RX}(dci) + P_i.(T_{WDC}(y_1, y_2, \ldots, y_n) + T_{wDC2DS})) \quad (8)$$

The P_{RX} and P_i in (8) denotes the power consumed during the reception of DL packet from the network and the power consumed when UE is in standby mode, respectively. The duration of downlink time and reception time of packet is given by $T^{DL}_{Gap}(y) and T_{RXdl}(y)$. Whereas $N_{seg}(y)$ defines the number of segments and $T_{RX}(dci)$ defines the reception time of downlink control information. After the termination of downlink control information, the commencement of NPDSCH transmission is denoted by T_{wDC2DS}.

Using MATLAB, PSO algorithm has been applied in the current work to optimize the $E_{rx}(y)$. From (8) it is clearly visible that $E_{rx}(y)$ is dependent on the various described parameters. The above defined parameters in (8) are either constraint or non-constraint in nature. The two non-constraint parameters $P_{RX}$and H_{RLCMAC} has been selected in such a way that $E_{rx}(y)$ becomes minimum. Similarly, P_{RX} and N_{SF} has been optimized simultaneously to receive minimum $E_{rx}(y)$.The proposed PSO algorithm has been defined with the help of flow diagram in Fig. 2.

PSO gets influenced by several control parameters, such as accelerating coefficient, number of iterations, swarm size and inertia weight. Initially the swarm size of PSO is decided and initialized. Swarm size is problem dependent. Smaller swarm size provides optimal solutions. In the proposed work, the swarm size is taken as 40. The acceleration constant (x_1 and x_2) has been given the value of 1.4455 each. The acceleration constant defines the social and cognitive components along with overall velocity of particles. The inertia weights control the behaviour of PSO based on motion of particles and search space. The initial and final value of weight has been kept as 0.9 and 0.4 respectively. To reach the optimal solution, number of iterations are chosen based on problem and computational complexity. The number of iterations considered is 300. After initializing the PSO parameters, objective function is defined and evaluated for the considered swarm size. During each particle, the position and global best solution is updated to find the optimized value of energy. In the swarm, the parameter values represents the position of that particle. At each iteration, the position of each particle is updated using the velocity of the particle. Continuous changes in each model parameter, at each iteration, occurs due to particle velocity and direction.The performance evaluation of PSO has been analysed by comparing the optimized and non-optimized energy based on the selection of NB-IoT parameters such as P_{RX}, $N_{SF}$and H_{RLCMAC}using the MATLAB plots. The next section discusses about the simulation results and the performance analysis of the proposed model.

5. Simulation and results

The energy consumption of NB-IoT has been simulated and analysed in this section with the help of objective function defined in (8).To save energy after an interval of discontinuous NPDSCH, the UE moves to power saving state and moving of UE to power saving state occurs periodically. Thetime period, $T_{WDC}(y_1, y_2, \ldots, y_n)$, required till the

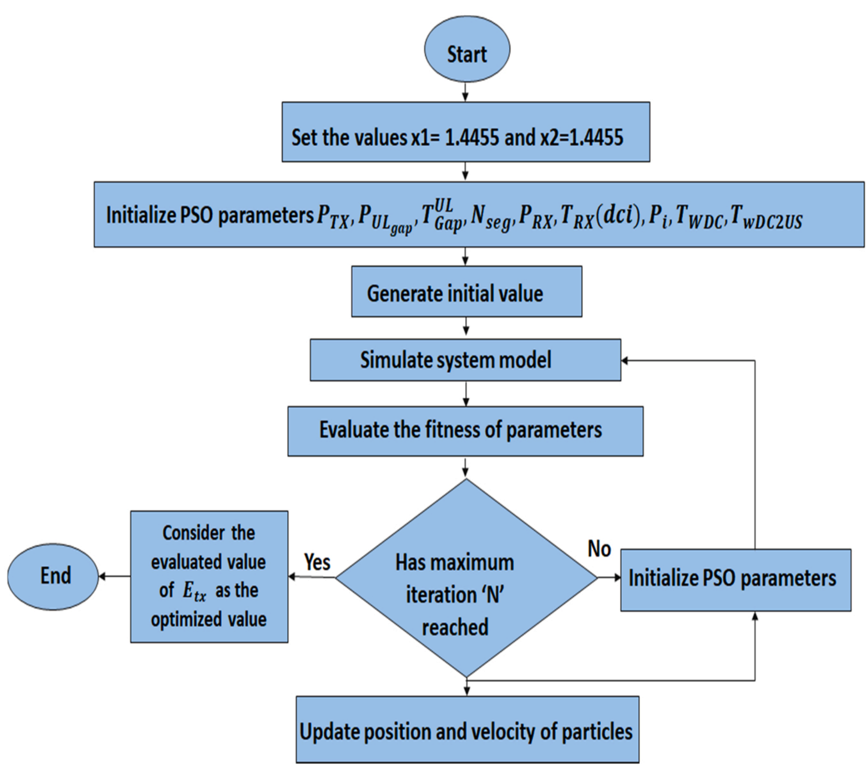

Fig. 2. Proposed particle swarm optimization algorithm [22].

arrival of next power saving state is known as the waiting period. To evaluate the energy consumption during the reception of DL packet, the simulation parameters given in Table 3 were involved-

The energy consumption of received downlink signal determines the signal quality and system efficiency. It helps in adapting the most effective transmission parameters like the TBS, number of repetitions and number of segments. In this paper, the PSO algorithm optimizes the $E_{rx}(y)$.

with respect to P_{RX}, $N_{SF}$and H_{RLCMAC}. On using PSO algorithm, firstly,P_{RX} and H_{RLCMAC} has been optimized successfully (optimization 1) with the optimal value of P_{RX} as 0.1355 Watts and H_{RLCMAC} as 16 bits has been obtained. These optimal values obtained after optimization using PSO has decreased the value of E_{rx}. Similarly, P_{RX} and N_{SF} has been optimized simultaneously (optimization 2) and on optimizing the optimal value of P_{RX}= 0.0295 Watts and N_{SF}= 6 has been obtained using PSO algorithm. On using these optimal values in Eq. (8) it has been concluded that the value of E_{rx} has decreased when compared to the non-optimized value. The comparison of non-optimized and optimized values of E_{rx} is given below in Table 4.

The plots in Fig. 3 shows the non-optimized and optimized value of E_{rx},when P_{RX} and H_{RLCMAC} has been optimized simultaneously (optimization 1). Also, optimization 2 where P_{RX} and N_{SF} has been plotted with respect to TBS. In present scenario, a large amount of data is required to be transmitted within minimal time. So, to increase the number of bits during each transmission, NB-IoT has adopted TBS. It is clearly visible that as the TBS increases, the energy consumption also increases. The MAC header length is responsible for signal synchronisation, and this results in an increase in power consumption during reception of DL packets. Thus, the H_{RLCMAC} has been optimized to 16bits to reduce the energy consumption in optimization 1. Similarly, in optimization 2, the N_{SF} has been reduced to 6 from 10 because sub-frames consume energy during data synchronization. Energy has been reduced drastically in optimization 2 as compared to optimization 1.

In Fig. 4 both the optimizations are carried out with respect to number of repetitions. It is evident that as the number of repetitions increases, the energy consumptions also increases rapidly because repetitions reduces the complexity and increases the coverage. It also increases the signal quality and error detection during transmission. Covering the large area and data, more energy is required. Thus, the optimizations are carried out by optimizing the number of sub-frames, received power and header length. And due to optimizations, the energy has reduced effectively in optimization 2 where we considered the number of sub-frames and received power.

As discussed earlier, the number of segments considered in the proposed work is 7. Fig. 5 shows the non-optimized value and optimized value of E_{rx},with respect to number of segments. The number of segments and sub-frames are directly proportional to the time consumed during DL packet reaction and DL transmission gap. As the reception time increases, the E_{rx} will also increase. But since the parameters that

Table 3
Simulation Parameters [8].

Simulation Parameter	Value
Reception time of downlink control information, $T_{RX}(dci)$	1.428 ms
Length of RLC/MAC header,H_{RLCMAC}	32 bits
Power consumed due to the reception of data from the network by the UE, P_{RX}	215 mW
Power consumed when UE is in standby mode,P_i	17.8 mW
Number of sub frames, N_{SF}	10
Length of downlink packet, L_y	472 bits
Commencement of NPDSCH transmission after the termination of linked downlink control information, T_{wDC2DS}	5 ms
Population size in PSO	40
Final inertial weight in PSO (w1)	0.4
Initial inertial weight in PSO(w2)	0.9
Number of iterations in PSO($I_t$max)	300
Acceleration constant (C_1, C_2)	1.4455,1.4455

Table 4
Non-optimization and Optimization Comparison Table.

S. No.	Value of E_{rx} (in Joules) before optimization	Value of E_{rx} (in Joules) after optimization of P_{RX} and H_{RLCMAC}	Value of E_{rx} (in Joules) after optimization of P_{RX} and N_{SF}
1	0.0248	0.0041	0.0115
2	0.0186	0.0027	0.0075
3	0.0224	0.0034	0.0088
4	0.0323	0.0048	0.0124
5	0.0506	0.0075	0.0193
6	0.0832	0.0124	0.0318
7	0.1416	0.0212	0.0541

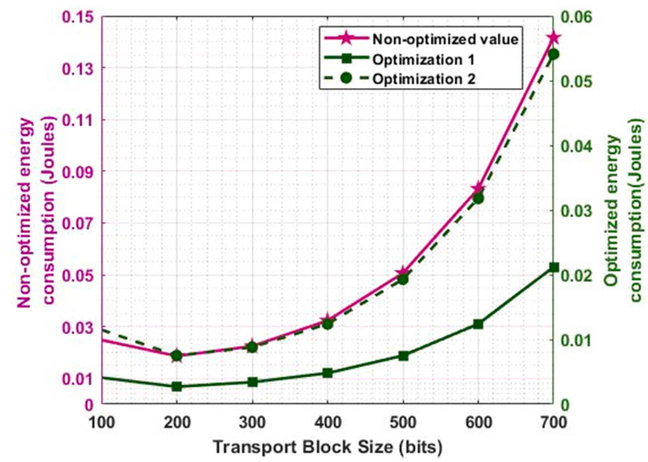

Fig. 3. Non-optimized and optimized energy consumption for downlink packet reception with respect to transport block size.

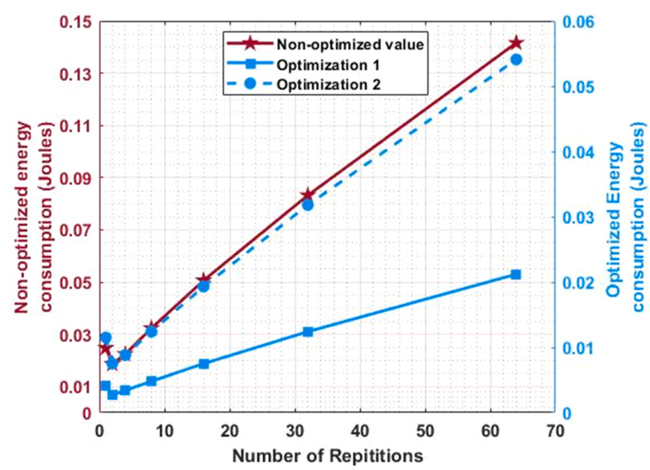

Fig. 4. Non-optimized and optimized energy consumption for downlink packet reception with respect to number of repetitions.

are being optimized in both the case are P_{RX}, H_{RLCMAC} and N_{SF}, a trade-off exists. The proper selection of the described free-parameters can gradually affect the energy consumption. Increase in number of segments reduces the energy utilization, making it suitable for many IoT applications.

Fig. 6 shows the comparative bar graph of non-optimized value of E_{rx} and both the optimization value of $E_{rx}$with respect to transport block size (TBS). It is observed that optimization 2 where the P_{RX} and N_{SF} has been optimized has very effectively reduced the energy consumption as compared to optimization 1.

Also, when P_{RX} and H_{RLCMAC} has been optimized simultaneously

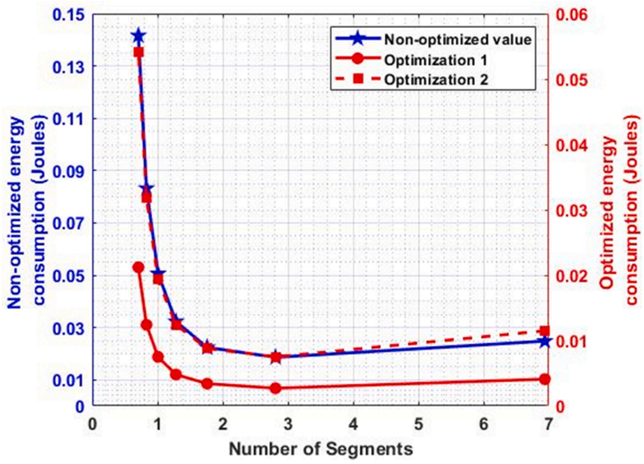

Fig. 5. Non-optimized and optimized energy consumption for downlink packet reception with respect to number of segments.

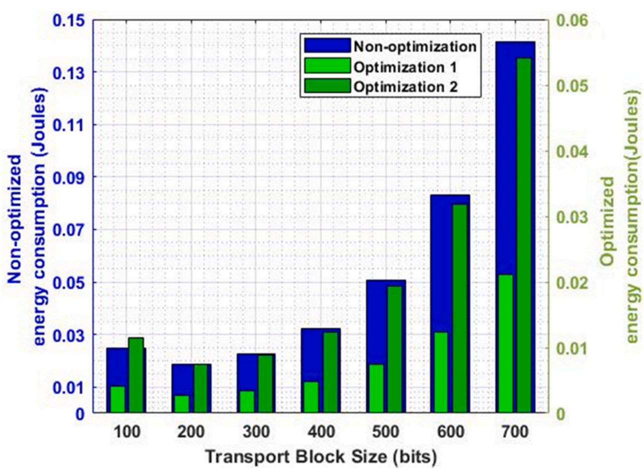

Fig. 6. Comparative bar graph of non-optimized and optimized energy consumption for downlink packet reception.

(optimization 1) the average energy efficiency of 84.98% is attained and when P_{RX} and N_{SF} has been optimized simultaneously (optimization 2) the average energy efficiency of 61.07% is attained.

6. Conclusion

NB-IoT potential in terms of increased number of heterogenous devices, extended coverage and low energy consumption has made it the most prominent in different fields of IoT applications. Anticipating the future requirements, NB-IoT technology has been discussed in detailed in the proposed work based on its energy consumption during downlink. In this paper, the mathematical model for energy requirement by UE to receive a downlink packet has been analysed. The major parameters that affect the energy utilization in NB-IoT during downlink of packets are transport block size, number of repetitions and number of segments. The free-parameters used for optimization are received power, number of sub-frames and length of MAC header. By using PSO algorithm, the energy required to receive a downlink packet by UE has been optimized. Using PSO first P_{RX} and H_{RLCMAC} has been optimized simultaneously (optimization 1)and then similarly P_{RX} and N_{SF} has been optimized simultaneously (optimization 2). After optimization, it has been observed that the energy required by UE to receive a downlink packet in NB-IoT is decreased and the overall average energy efficiency of the system has been increased. When P_{RX} and H_{RLCMAC} has been optimized simultaneously (optimization 1) it is calculated that the percentage average energy efficiency is 84.98%. Similarly, when P_{RX} and N_{SF} has been optimized simultaneously (optimization 2)it is calculated that the percentage average energy efficiency is 61.07%. The results have been compared critically before and after optimization.

In future, this enhanced energy efficiency can be implemented in IoT applications such as smart homes, smart vehicles, smart grids etc. Also, the energy consumption can further be improved using the different modulation techniques incorporating low-energy based MAC protocol.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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