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DUROCOM: energy efficient dual radio communication protocol for battery constrained IoT networks

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ABSTRACT

Emerging battery-constrained IoT devices face significant communication challenges due to frequent power interruptions and limited time synchronization. Traditional low-power wireless protocols are limited by intermittent energy availability and lack of precise timing. While the IoT offers many advantages, it also poses significant challenges including energy constraints, which may lead to a limited lifespan of IoT devices. To overcome these issues, a novel DUal RadiO COMmunication (DUROCOM) protocol has been proposed. It provides dependable communication between a receiver and several devices by synchronizing them using two low-power wake-up radios. The Reptile Search Algorithm is used for protocol optimization to adjust the data rate. The efficacy of the framework is evaluated using metrics namely throughput, energy consumption, power control efficiency, and latency. The DUROCOM technique improves the energy efficiency by 7.91%, 43.57%, and 66.44% and Network Lifetime by 4.37%, 10.88%, and 18.51% better than the existing Quantum-SSA-Markov Model, HDS, and BaMbI approaches.

1. Introduction

An IoT allows billions of smart devices to connect seamlessly across a wide range of applications such as industrial automation, smart cities, healthcare, and environmental monitoring [1]. However, many IoT devices are battery-powered and operate under severe energy constraints, making efficient communication a significant challenge [2]. Existing wireless communication protocols are primarily designed for devices with stable power sources, leading to inefficiencies when applied to battery-constrained networks [3]. These limitations often result in frequent communication failures, increased latency, and reduced network reliability, hindering the full potential of IoT deployments [4,5]. Table 1 lists the acronyms used in the research work. (Table 2).

A major challenge in battery-constrained IoT networks is ensuring continuous and reliable communication despite intermittent power availability [6]. Since many devices operate with limited energy reserves, maintaining synchronization and connection stability becomes difficult [7]. Conventional low-power communication protocols typically rely on predefined duty cycles and fixed transmission schedules, which fail to adapt to varying energy levels and dynamic network conditions [8]. As a result, devices experience inefficient energy usage, leading to shorter operational lifetimes and increased data transmission delays [9]. Addressing these issues requires an adaptive communication strategy that can dynamically optimize energy consumption while ensuring seamless data exchange [10].

To enhance energy efficiency in IoT networks, researchers have explored various techniques, such as duty cycling, wake-up radios, and

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Table 1
List of abbreviations.

Acronym	Definition
IoT	Internet of Things
DUROCOM	DUal RadiO COMmunication
TP	Transmission Power
CI	Connection Interval
RSA	Reptile Search Algorithm
DR	Data Rate
PDR	Packet Delivery Ratio
EC	Energy Consumption
NL	Network Lifetime
RIS	Reconfigurable Intelligent Surface
BRT	Battery Recharging Time
BaMbI	BAttery-free Mobile Interactive device
GPS	Global Positioning System
HDS	Heterogeneity-aware Dual-interface Scheduling
WiFi	Wireless Fidelity
RF	Radio-Frequency
CRN	Cognitive Radio Network
SSA	Salp Swarm Algorithm
LoRa	Low-rank adaptation
DT	Digital Twin
DE	Differential Evolution
WUR	Wake-Up Radio
VoI	Value of Information
MSE	Mean Square Error
WakeMod	WUR Module
WupPkts	Wake-up Packets
RAPID	Reptile search Algorithm for Protocol optimization in IoT Devices
WupR	Wake-up Radio
MAC	Media Access Control
BLE	Bluetooth Low Energy
ES	Evolutionary Sense
OFS	Optimal Features Subset
ECI	Estimated number of CI
HCI	Host Controller Interface
QoS	Quality of Service
BS	Base Station
SNs	Sensor Nodes
RMSE	Root Mean Squared Error
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error

energy-aware routing [11]. These methods help reduce unnecessary energy expenditure but often introduce trade-offs between latency and network throughput [12]. Additionally, existing approaches do not effectively handle transient power outages, which are common in energy-harvesting or battery-dependent IoT devices [13]. The need for an optimized communication protocol that balances energy consumption, reliability, and network performance is significant for enhancing the longevity and effectiveness of battery-constrained IoT networks [14,15].

Another key concern in IoT communication is the impact of network topology and TP control on overall efficiency [16]. Traditional networks use static power levels and CI, which may lead to excessive energy consumption or underutilization of available resources [17]. An intelligent protocol that can dynamically adjust transmission metrics based on real-time network conditions and device energy levels is essential for improving communication efficiency [18,19]. By incorporating adaptive mechanisms, IoT devices can operate for extended periods without frequent battery replacements, making large-scale deployments more practical and cost-effective [20].

To tackle these issues, this paper provides DUROCOM, a novel DUal RadiO COMmunication protocol specifically designed for battery-constrained IoT networks.

- A novel dual-radio protocol employs the wake-up radio and a main transmission radio designed to enhance communication efficiency, enable efficient synchronization and communication between devices and the receiver in IoT networks.
- The protocol utilizes the RSA model for protocol optimization for dynamic adjustment of DR, TP, and CI to minimize EC, latency and improve the overall energy efficiency and network lifespan.
- A latency-aware routing framework that guides the selection of low-latency communication paths while ensuring minimal delay and high PDR.
- The efficiency of the suggested DUROCOM system has been examined using parameters such as throughput, EC, power control efficiency, NL, PDR, convergence analysis, network reliability, energy efficiency, and latency respectively.

The rest of this work is outlined as follows: In Section 2, the prior method is discussed. Section 3 provides the developed approach in this study. The experimental progress, validating the assertions of this research has been elaborated in Section 4, along with the presentation of results. Finally, Section 5 delivers the experiment's conclusions.

Table 2
Comparison of existing techniques.

Author & Year	Methods	Advantages	Disadvantages	Result comparison
Derbas et al., 2024 [21]	RIS-assisted routing technique	Improves routing	Limited scalability	DUROCOM improves energy efficiency
Adam et al., 2024 [22]	BaMbI	Reduces GPS energy consumption	Limited to GPS-based systems	DUROCOM achieves greater energy reduction
Hudda et al., 2024 [23]	Node degree-aware clustering	Better cluster stability	Ignores dynamic network latency	DUROCOM is reducing both latency and energy use
Chen et al., 2024 [24]	HDS	Achieve the delay constraint	Complexity in interface coordination	DUROCOM achieves higher throughput and lower EC
Sharma, M. and Sarma, N., 2024 [25]	RF energy harvesting in CRN	Accurate energy optimization	Limited real-world IoT use	DUROCOM provides broader energy-aware communication
Algarni, S. and El-Samie, F.E. A., 2025 [26]	distributed edge computing solution	Enhances scalability and availability	High cost	DUROCOM minimizes energy and latency
Jabberi et al., 2025 [27]	Quantum-SSA-Markov Model	Scalable localization	High computational overhead	DUROCOM outperforms in EE by 7.91 %, with faster convergence using RSA
Chen et al., 2025 [28]	Multi-hop LoRa optimization	Saves transmission time and energy	Protocol-specific limitations	DUROCOM adapts across dynamic IoT networks with adjustable TP/DR
Prauzek et al., 2025 [29]	DE-optimized DT controller	Improves solar-based energy usage	Relies on external energy predictions	DUROCOM offers real-time adaptation
Dunsin 2025 [30]	An energy-efficient microservices architecture	Reduces component energy	Focus on middleware, not routing	DUROCOM directly optimizes physical-layer communication
Deshpande et al., 2024 [31]	Content-based WUR	Increases battery lifetime	Requires accurate VoI estimation	DUROCOM achieves broader applicability with dynamic optimization
Schulthess et al., 2025 [32]	WakeMod	Ultra-low power consumption	Limited to hardware integration	DUROCOM adds protocol adaptability and routing intelligence over WURs

2. Literature review

In recent years, a number of research have utilized a variety of techniques for battery-constrained IoT networks. A number of the contemporary evaluation techniques are discussed in the part that follows, along with some of their drawbacks:

In 2024, Derbas et al [21] introduced a new RIS-assisted routing technique for wireless networks with multi-hop energy harvesting. Every hop on the selected path is given a channel by the protocol. It includes a rate calculation system that accounts for channel characteristics, BRT, and harvested power. MATLAB simulations are used to assess and compare the suggested method with the benchmark, the Min hop scheme, proving its superior performance.

In 2024, Adam et al [22] introduced BaMbI a low-cost power and communication architecture for battery-free personal communication devices. The objective is to significantly minimize the EC of GPS-based navigation to ensure usability in BaMbI and similar devices. They build a reference hardware platform and conduct a series of experiments on the prototype, simulating different scenarios and analyzing the results. The overall findings show the feasibility of the model in decreasing the energy consumption of navigation in BaMbI.

In 2024, Hudda et al [23] proposed two variants of a new model for energy-efficient communication in constrained IoT networks. By doing away with the need for re-election procedures, one version takes the node degree into account while the other does not to increase round speed. Additionally, the authors tested the efficacy of the developed model based on various factors including the number of clusters, operating nodes, remaining energy, and transmission energy. The results of this comparison are promising, as the suggested variant with node degree outperforms other approaches.

In 2024, Chen et al [24] suggested a Heterogeneity-aware Dual-interface Scheduling (HDS) approach to enable energy-efficient and delay-constrained data collection in a tree-based IoT network, where every device has both a WiFi and a ZigBee interface. According to experimental data, with a modest delay limitation, HDS's EC is 80.3 % and 43.6 % less than that of an innovative dual-interface system and the conventional power saving protocol, respectively. It is also more than 98.6 % of data packets that meet the delay constraint.

In 2024, Sharma, M. and Sarma, N., [25] investigated the use of radio-frequency (RF) energy harvesting in Cognitive Radio Networks (CRNs) as a way to greatly increase mobile devices' battery life. To optimize energy harvesting, they suggest a combined time-switching and power-splitting method that yields a 97.7 % accurate sub-optimal solution in comparison to the ideal outcome.

In 2025, Algarni, S. and El-Samie, F.E.A., [26] implemented a new distributed edge computing solution to allow IoT applications across dense networks while meeting the stated requirements. The suggested paradigm improves the availability, scalability, and dependability of the network. We provide the distributed nodes' energy model and the network model. An IoT testbed was created to assess the built network.

In 2025, Jabberi et al [27] presented a novel hybrid model that integrates quantum mechanics for state representation, Markov processes for predictive modeling, and the Salp Swarm Algorithm (SSA) for optimizing nodal positions and speeds. Experimental results confirm that this innovative approach provides a scalable and reliable solution for next-generation IoT systems, particularly in scenarios that require robust real-time localization.

In 2025, Chen et al [28] suggested a new method for LoRa transmission that includes parameter analysis and formula derivation. By utilizing the benefits of both LoRa protocols and multi-hop technologies, this method enables data to swiftly flow from the center of a region to every device. It can save about 87.4 % of the time when transmitting data downstream. Furthermore, simulation research shows that, when compared to the benchmark techniques, the suggested algorithm may save at least 12.61 % of the transmission energy under limitations.

In 2025, Prauzek et al [29] offered a new digital twin (DT) idea for dynamic optimization of IoT node behavior. The controller of the model is based on fuzzy rules and is optimized using the differential evolution (DE) technique. By utilizing 4 years of solar data gathered from various geographic regions, the suggested approach enhances energy utilization by 11 % in comparison to conventional energy management techniques.

In 2025, Dunsin [30] developed an energy-efficient microservices architecture for IoT applications. The proposed solution addresses energy constraints and extends device longevity by using modular, resource-aware designs and lightweight protocols. Performance was not compromised by the middleware's ability to reduce by a significant margin the energy consumption of the components involved. Results showed significant potential of the modular architecture, together with energy-aware algorithms and lightweight protocols, in boosting sustainability and scalability of IoT ecosystems.

In 2024, Deshpande, A.A., et al., [31] created a content-based WUR that monitors the process perceived by the sensors and only activates the sensor when the VoI of its estimated update exceeds a threshold that is conveyed by the poll. It demonstrates that content-based WUR can offer fine-grained control over this trade-off and considerably extend the node's battery life with a negligible MSE rise by examining the trade-off between the tracking error and the sensors' battery life.

In 2025, Schulthess, L., et al., [32] introduced the WakeMod open-source wake-up transceiver module for the ISM band operating at 868 MHz. Ultra-low power consumption and ease of integration are key design features. WakeMod maintains responsiveness with a sensitivity of −72.6dBm while achieving a low idle power consumption of 6.9uW. WakeMod provides a workable solution for long-term, energy-constrained IoT deployments that need on-demand, low-latency communication.

2.1. Research gap

After a thorough review of the literature, the following research gaps were identified in relation to the developed approach:

- Although there have been a number of advances made in battery-constrained IoT networks, there are still a number of challenges with battery-constrained IoT networks in smart cities. Research continues to be done to develop the novel DUal RadiO COMmunication (DUROCOM) protocol specifically designed for battery-constrained IoT networks.
- The existing energy-efficient communication methodologies depend on several design constraints. Most of the methods employ traditional scheduling, duty cycling, or static transmission control mechanisms in battery-constrained IoT networks. However, the literature review reveals that dynamic protocol optimization using intelligent algorithms can significantly reduce energy consumption and improve communication reliability in real-time applications.

The proposed DUROCOM methodology overrides such drawbacks by reducing the delay, inefficient energy utilization, and scalability, as well as the inability to handle dynamic network conditions. To address these issues, the proposed DUROCOM incorporates dual wake-up radio architecture, adaptive transmission control, and real-time protocol optimization using RSA. These enhancements reduce the end-to-end communication delay, minimize energy consumption and processing overhead, and allow the system to scale efficiently without compromising performance. The proposed DUROCOM approach is provided in the following section.

3. Durocom model

In this study, a novel DUal RadiO COMmunication (DUROCOM) protocol has been designed for battery-constrained IoT networks.

Initially, smart city environments consist of numerous interconnected IoT devices, which are equipped with a dual-ratio

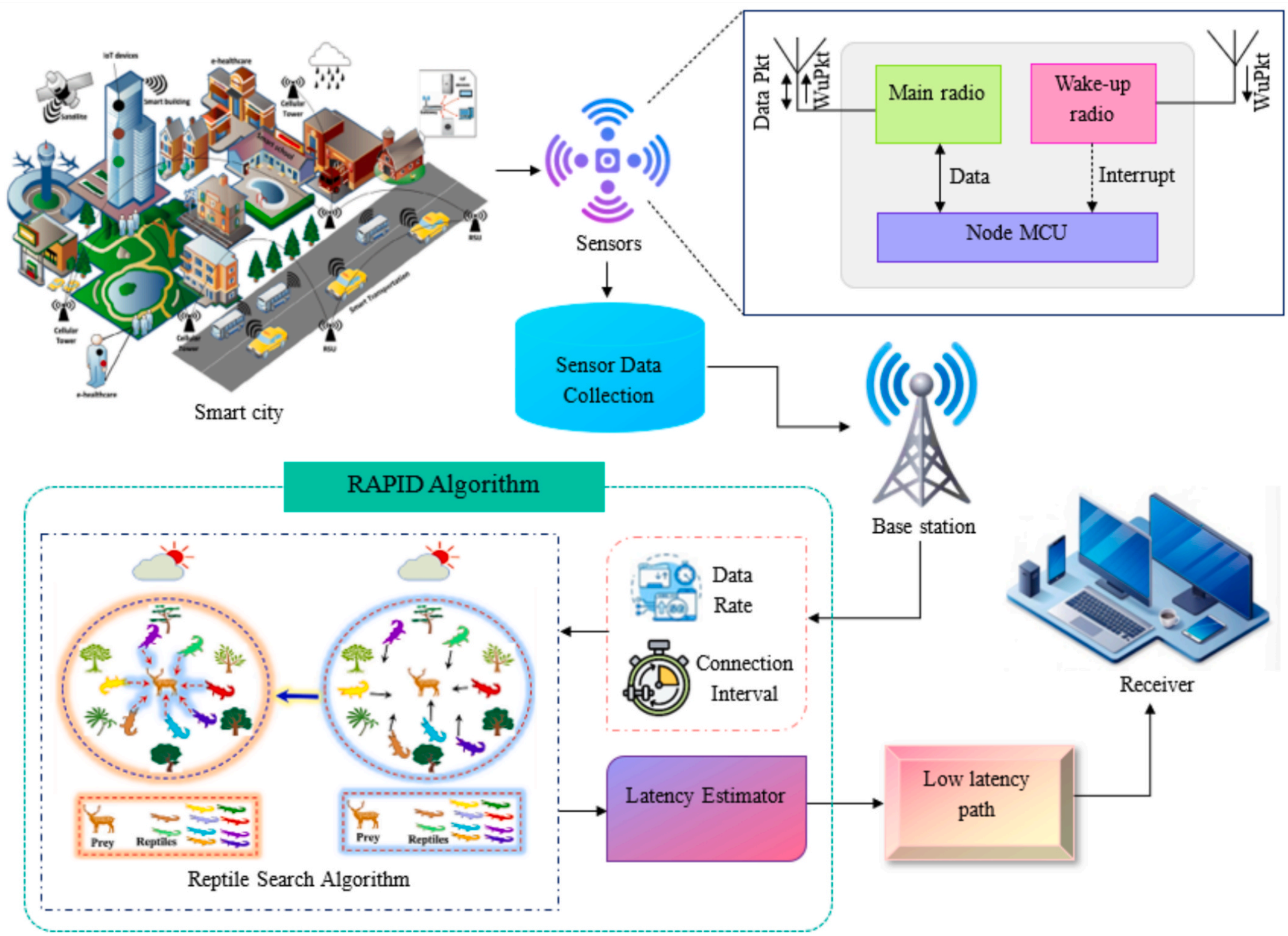

Fig. 1. Proposed DUROCOM model.

architecture [33]. It comprises a main radio for low-latency communication, which handles high-throughput data transmission, and a wake-up radio is a low-power receiver that remains active to detect incoming wake-up packets (WupPkts) and triggers only when communication is required to save energy. The NodeMCU is responsible for coordinating wake-up signaling, packet routing, and execution of the DUROCOM protocol logic. These sensors forward the data to a centralized sensor data collection unit and then to the base station. Then the data such as DR and CI are undergoing the Reptile Search Algorithm for Protocol optimization in IoT Devices (RAPID) phase. Then the RSA [34] algorithm is utilized for protocol optimization for minimizing latency, optimizing routing paths, adjusting DR and TP, and reducing EC to adapt to real-time network and energy conditions. These optimized metrics are monitored for network delays to the RAPID module by a latency estimator [35], which uses Bluetooth commands to measure end-to-end delay and informs the routing strategy. Based on these metrics, the system dynamically selects low-latency paths for data transmission. Finally, the optimized data is delivered to IoT devices like smartphones and computers to enable timely and efficient smart services across the city. The proposed DUROCOM model is explained in Fig. 1.

3.1. Dual-radio architecture

A very low-power radio receiver known as a Wake-up Radio (WupR) continuously scans the wireless channel and sends out an interrupt signal if it identifies the presence of a Wake-up Packet (WupPkt). Two modes of operation are supported by a typical WupR: broadcast mode, where a single WupPkt activates numerous WupRs, and addressable

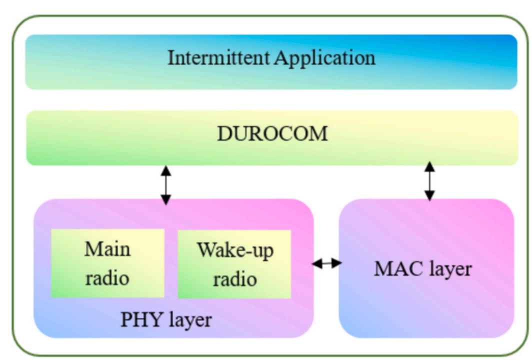

Fig. 2. Communication stack for proposed model.

mode, where a WupPkt carrying its address pattern or ID activates each WupR separately. Because main radios may generate WuPkts in addition to transmitting data, the WupR is frequently employed in conjunction with a main radio, eliminating the requirement for an independent WupPkt transmitter.

A WupR is set up to continually track the network channel when the primary radio is turned off or in sleep mode. To eliminate idle listening overheads on the main radio, the WupR receives an addressed (ID-based) or broadcast WupPkt, which triggers an interrupt (for data transfer) to activate the main radio. Fig. 2 illustrates the dual-radio architecture [33] utilized by WupR MACs of asynchronous protocols to

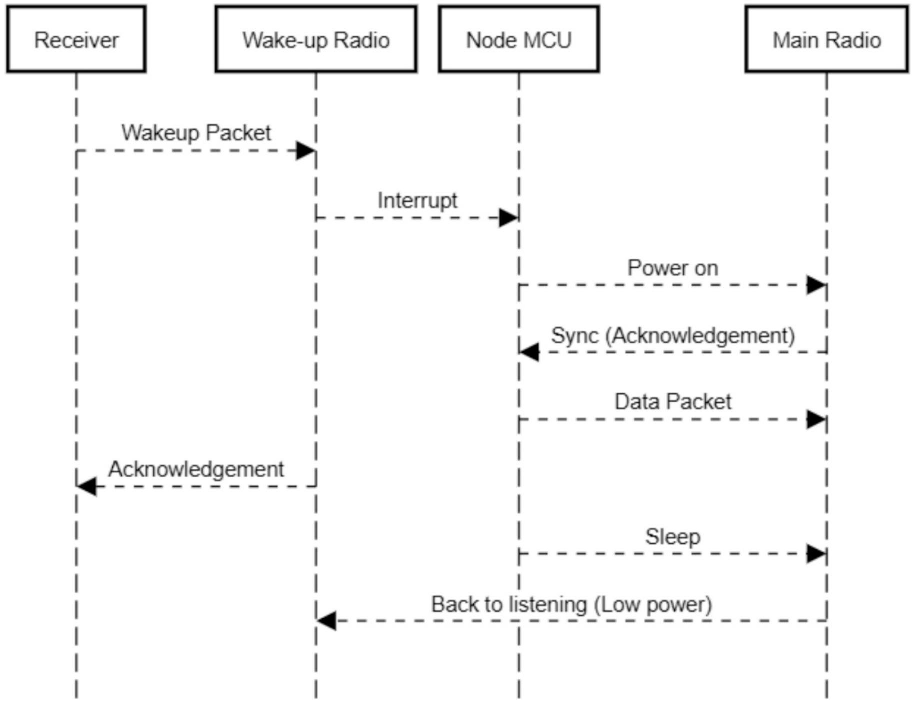

Fig. 3. Wake_and_Sync communication flow diagram.

boost performance.

3.1.1. Wake_and_Sync

The receiver wakes up and synchronizes all of the network's battery-less nodes with a WupPkt broadcast to start the communication cycle. The WupPkt sent by the receiver's primary radio functions both as an advertisement for unpaired nodes and a synchronization signal for already paired nodes.

The WupPkt transmission period can also be impacted by whether pattern correlation is enabled or whether the WupPkt contains additional data. Pattern correlation reduces the amount of spurious wake-up events, which is beneficial for asynchronous WupR MAC protocols that prefer selective ID-based wake-ups. After sending the WupPkt, the receiver advances to the discovery stage. Prior to receiving a WupPkt, every node in the network should be either asleep or harvesting energy to power up. While unconnected nodes move on to the Discovery phase, connected nodes synchronize their timings with the receiver upon waking up and go back to sleep until the beginning of their time slots. Fig. 3 shows the sequence flow diagram of Wake_and_Sync communication.

3.2. RAPID algorithm

In this phase, DR and CI are the output from the base station. The goal of the DR and CI is to reduce energy usage while preserving a respectable level of network quality. It is challenging to use a constant CI for BLE in a dynamic channel environment. To reduce energy usage, a CABLE was built that monitors the packet error rate and modifies the connection time accordingly. Bluetooth 5′s throughput and transmission range were measured for different DRs, showing that a high DR increases throughput while a low DR increases transmission range. The RSA algorithm uses these two parameters as inputs to optimize the protocol: DR and CI.

3.2.1. Reptile search algorithm (RSA)

In this work, RSA [34] is utilized for protocol optimization for minimizing latency, optimizing routing paths, adjusting DR and TP, and reducing EC. RSA is a new optimization method that draws inspiration from crocodiles' surroundings and hunting tactics. Fig. 4 illustrates the algorithm's two mechanisms, which are separated into the global search phase, which is symbolized by the encircling behavior [35]. The first and

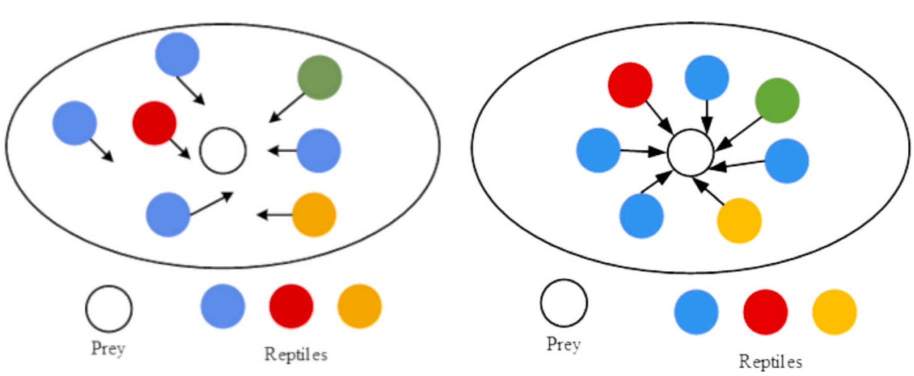

Fig. 4. RSA Encircling phase.

second halves of the iteration are when these mechanisms take place, respectively. The features of these two mechanisms are covered in the next two subsections.

The DR, TP, and the CI are input to this RSA algorithm. The two primary operators used in the RSA global exploration phase high walking and belly walking help locate regions with a high prey density and streamline the hunting phase. During the first and second halves of the exploration phase, high walking and belly walking take place, respectively. Consequently, as shown in Eq. (1), the crocodile positions are updated.

$$-f_{u,v}(t+1) = \begin{cases} -f_{u,v}(t).\omega.Bst_v(t) - \left[rand_{\in[1,S]}.ReFun_{u,v}(t)\right], t \le \dfrac{t}{4} \\ ES(t).Bst_v(t).y_{\left(rand_{\in[1,S]},v\right)}, t \le \dfrac{2t}{4} and t > \dfrac{t}{4} \end{cases} \tag{1}$$

The best solution for v^th^ feature is represented by $Bst_v(t)$, the metric ω controls the exploration accuracy and is set as 0.1, $f_{u,v}(t)$ at index u, v corresponds to the v^{th} position of best solution discovered in the current iteration t, and the hunting operator for the v^{th} feature in the ith solution is represented by $s_{u,v}$. Here, the best solution is described as the optimal path.

Eq. (2) is utilized to calculate Evolutionary Sense ES(t), which is the probability ratio that declines from 2 to − 2 over iterations. The number between 1 and S that is employed to choose at random one of the possible candidate solutions is indicated by $rand_{\in[1,S]}$.

$$s_{u,v} = Bst_v(t) \times P_{u,v} \tag{2}$$

where $s_{u,v}$ is the v^{th} position of a hunting operator for the u^{th} solution, $P_{u,v}$ is calculated as follows (3), which is the percentage difference between the v^{th} value of the optimal path and its equivalent value in the current path:

$$P_{u,v} = \varphi + \frac{y_{u,v} - \tau(y_u)}{Bst_v(t) \times (UpL_v - LowL_v) + \varepsilon'} \tag{3}$$

where φ illustrates a sensitive parameter that controls the efficacy of the exploration, $\tau(y_u)$ represents the average solutions, and ε represents a modest floor value. UpL_v and $LowL_v$ are the upper and lower boundaries of the v^{th} position. This expression is stated as follows (4,5):

$$\tau(y_u) = \frac{1}{s}\sum_{v=1}^{s} y_{u,v} \tag{4}$$

$$ES(t) = 2 \times rand_{\in\{-1,1\}} \times \left(1 - \frac{1}{t}\right) \tag{5}$$

where the value 2 is multiplied to produce correlation values in the range [0, 2] and $rand_{\in\{-1,1\}}$ is a random integer number between {−1, 1}. In the last two phases, RSO exploits (hunts) the search space to get closer to the optimal solution through cooperation and coordination. The following Eq. (6) can be used by the candidate solution to update its value during the exploitation phase:

$$y_{u,v}(t+1) = \begin{cases} rand_{\in\{-1,1\}}.Bst_v(t).P_{u,v}(t), t \le \dfrac{3t}{4} and t > \dfrac{2t}{4} \\ \left[\varepsilon.Bst_v(t).s_{u,v}(t)\right] - \left[rand_{\epsilon\{-1,1\}}.R_{u,v}(t)\right], t \le T and t > \dfrac{3T}{4} \end{cases} \tag{6}$$

In this context, when $t \le \frac{3t}{4}$ the encircling phase takes place, otherwise when $t < \frac{3t}{4}$, the hunting phase happens to find near/optimal solution. At each iteration, the quality of possible solutions is evaluated using the preset value. The algorithm stops after S iterations, and the candidate solution with the lowest value is the most OFS. The proposed DUROCOM model pseudocode of the RSA for protocol optimization is given in Algorithm 1.

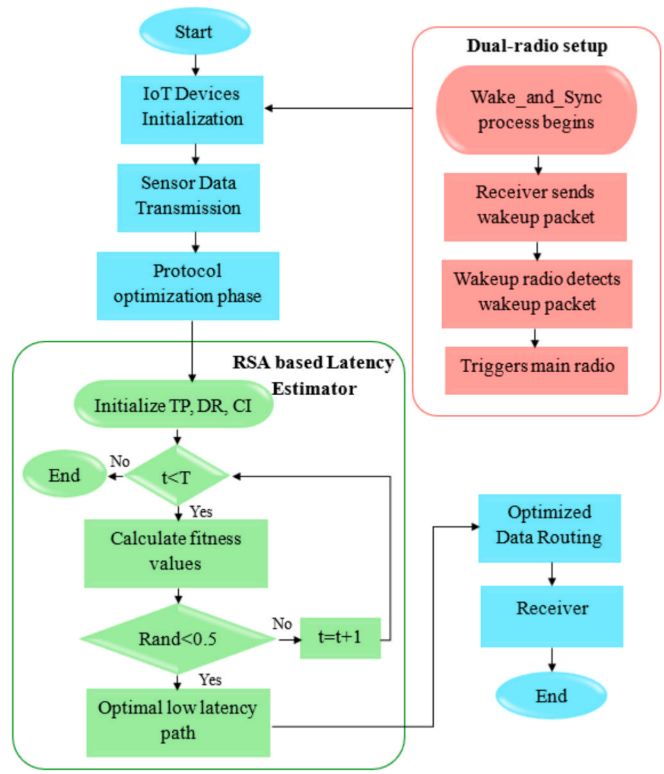

Fig. 5. Overall flow diagram of the developed DUROCOM approach.

Algorithm 1: Pseudocode of the RSA for protocol optimization

Initialization phase
Initialize RSA parameters such as DR, TP, CI
Randomly generate the initial positions X_i for $i = 1, 2, \cdots, N$
while (t < T) do
  Calculate Evolutionary Sense (ES) using Eq. (5)
  Update optimal path X_{bst} from current population
  For each path i in population do:
    For each dimension j of solution X_i do:
      Update the τ, R, and P values using Eqs. (4), (5), and (6)
      If $(t \le \frac{T}{2})$ and $(t \le \frac{T}{4})$:
$x_i,j(t+1) = Bst(t) - \tau_i,j(t) \times \beta - R_i,j(t) \times rand$
      Else if $(t \le \frac{3T}{4})$ and $(t > \frac{T}{2})$:
$x_i,j(t+1) = Bst(t) \times x_i,j(t) \times ES(t) \times rand$
      Else if $(t > \frac{3T}{4})$ and $(t > \frac{T}{2})$:
$x_i,j(t+1) = Bst(t) \times R_i,j(t) \times P_i,j(t) \times rand$
      Else:
$x_i,j(t+1) = Bst(t) - \tau_i,j(t) \times \varepsilon - R_i,j(t) \times rand$
      End for
    End for
    t = t + 1
End while
Return the optimal routing path

3.3. Latency estimator

For the latency estimator, we employ an anticipated number of CI (ECI) estimation scheme based on the host controller interface (HCI). This approach uses the standard HCI instructions of Bluetooth, thus it may be used with any device that supports Bluetooth. The master's host uses HCI_ACL_Data_Packet_Command to insert a data packet into the transmission buffer in order to communicate data over the BLE connection.

The master's controller releases the transmission buffer and transmits the HCI_Number_Of_Completed_Packets_Event to the host after the

Table 3
Simulation parameters for the DUROCOM protocol.

Parameters	Value
Simulation Area	100 m × 100 m
Number of nodes	500
Packet size	512 bytes
Node Density	0.005 to 0.020 nodes/m^2
Simulation Time	1000 s
Supply voltage	3.0 V
Transmit Power	30 mW (≈10 dBm)
Receive Power	15 mW
Idle Current (Main Radio)	1.2 mA
Sleep Current (WupR)	1.0 μA
Wake-up Time (WupR)	0.3 ms
Main Radio Wake-up Time	2 ms
Wake-up Radio Power	0.1 mW

data packet has been successfully sent to the slave. Thus, the time interval between a data packet entering the buffer and the buffer being released is known as s_{SU} and it is defined as follows (7).

$$s_{SU} = S_{FREE} - S_{ADD} \tag{7}$$

If s_{NV} is the length of the connection event, ECI_x, ECI at the i^{th} round, can be calculated as follows (8).

$$ECI_x = \left\lceil \frac{s_{SU} - s_{NV}}{S_{CI}} \right\rceil \tag{8}$$

The reason for subtracting s_{NV} is to compensate for the incorrect calculation of ECI_x due to processing when S_{ADD} overlaps with the connection event. These measurements are used by the system to dynamically choose low-latency data transmission routes. Finally, the optimized data is sent to IoT devices such as laptops and smartphones to enable smart services that are timely and effective throughout the city. Fig. 5 shows the overall working flow of the developed DUROCOM technique.

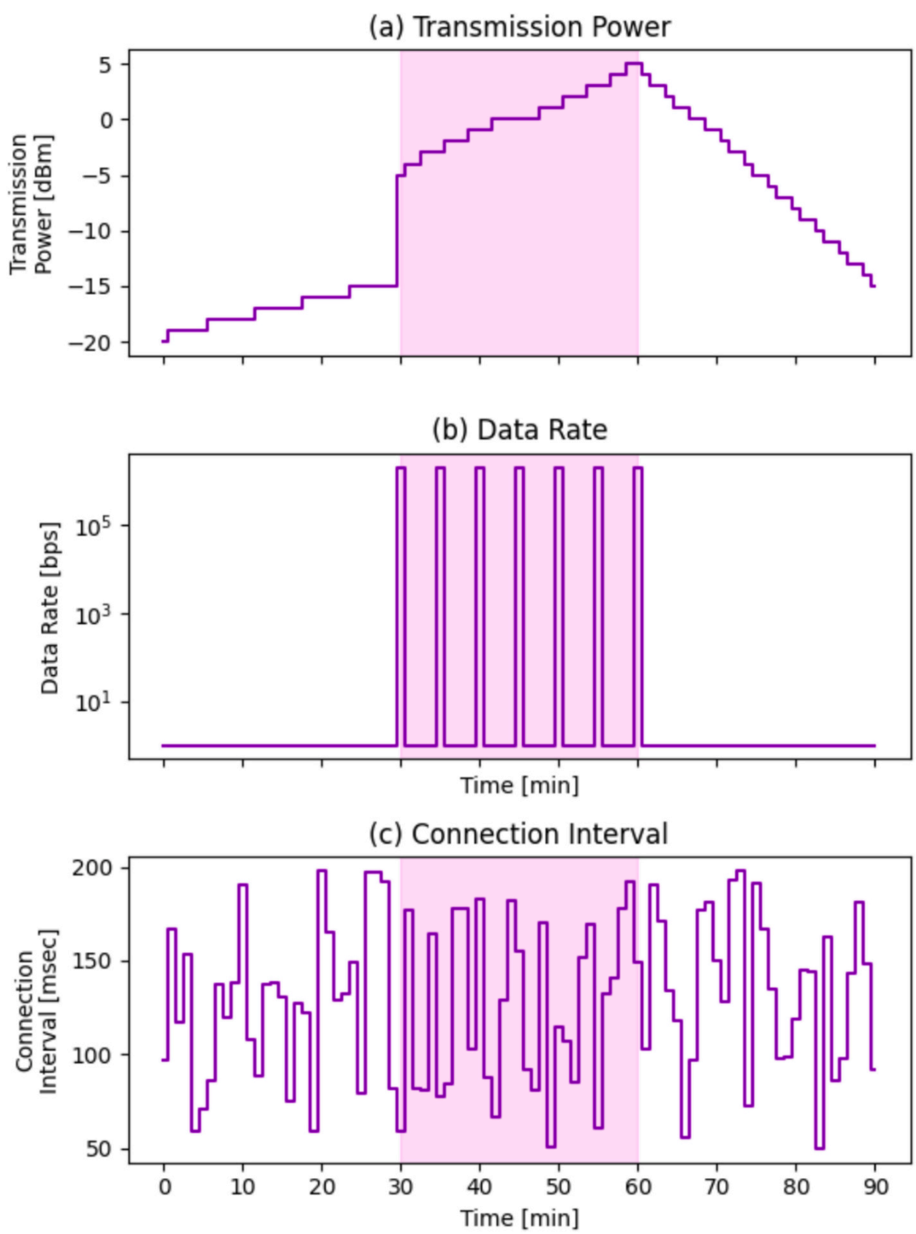

Fig. 6. Runtime Adaptation of DUROCOM Parameters.

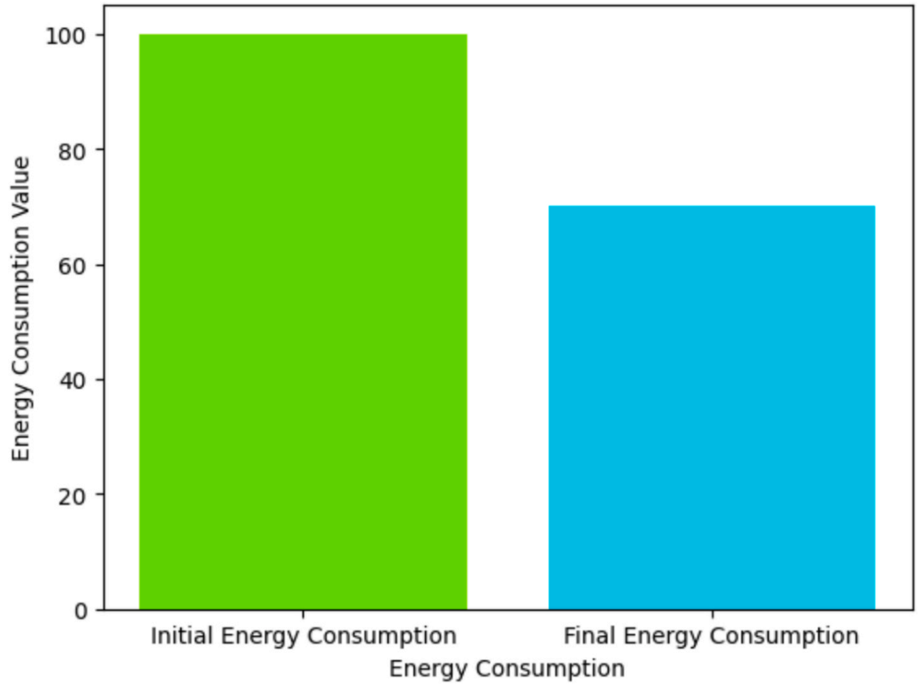

Fig. 7. Energy consumption comparison.

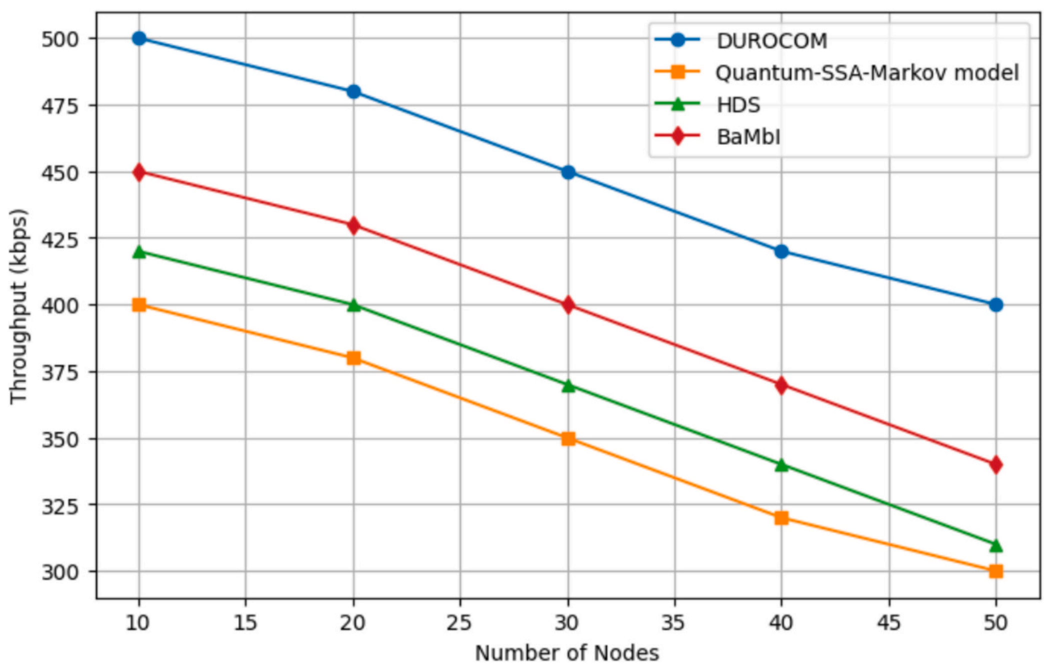

Fig. 8. Throughput comparison.

4. Results and discussion

In this section, the developed DUROCOM technique is examined in a Python simulator. In order to examine the efficacy of the developed DUROCOM framework, it has been compared with other techniques, including BaMbI [22], HDS [24], and Quantum-SSA-Markov Model [27]. A number of important efficacy metrics including throughput, energy consumption, power control efficiency, network lifetime, PDR, convergence analysis, energy efficiency, and latency, were evaluated to determine how well the DUROCOM method performed. The DUROCOM protocol parameters are shown in Table 3.

Fig. 6 displays DUROCOM's TP, DR, and CI over time. Figs. 6(a) and 6(b) demonstrate how, during the first 30 min, TP is progressively reduced to the lowest possible level while DR is raised to its highest possible level. This is due to network quality being sufficient to send packets with these worst parameters within the necessary latency. TP is primarily raised to enhance link quality when the channel state reduces (i.e., 30 to 60 min), and the DR could potentially drop from 2 Mbps to 1 Mbps at its maximum. As displayed in Fig. 6(c), the value of the CI is not impacted by the channel environment. This is due to DUROCOM's ability to change its TP and DR, which ensures consistent link quality in any channel situation. The CI adapts considerably more quickly than the

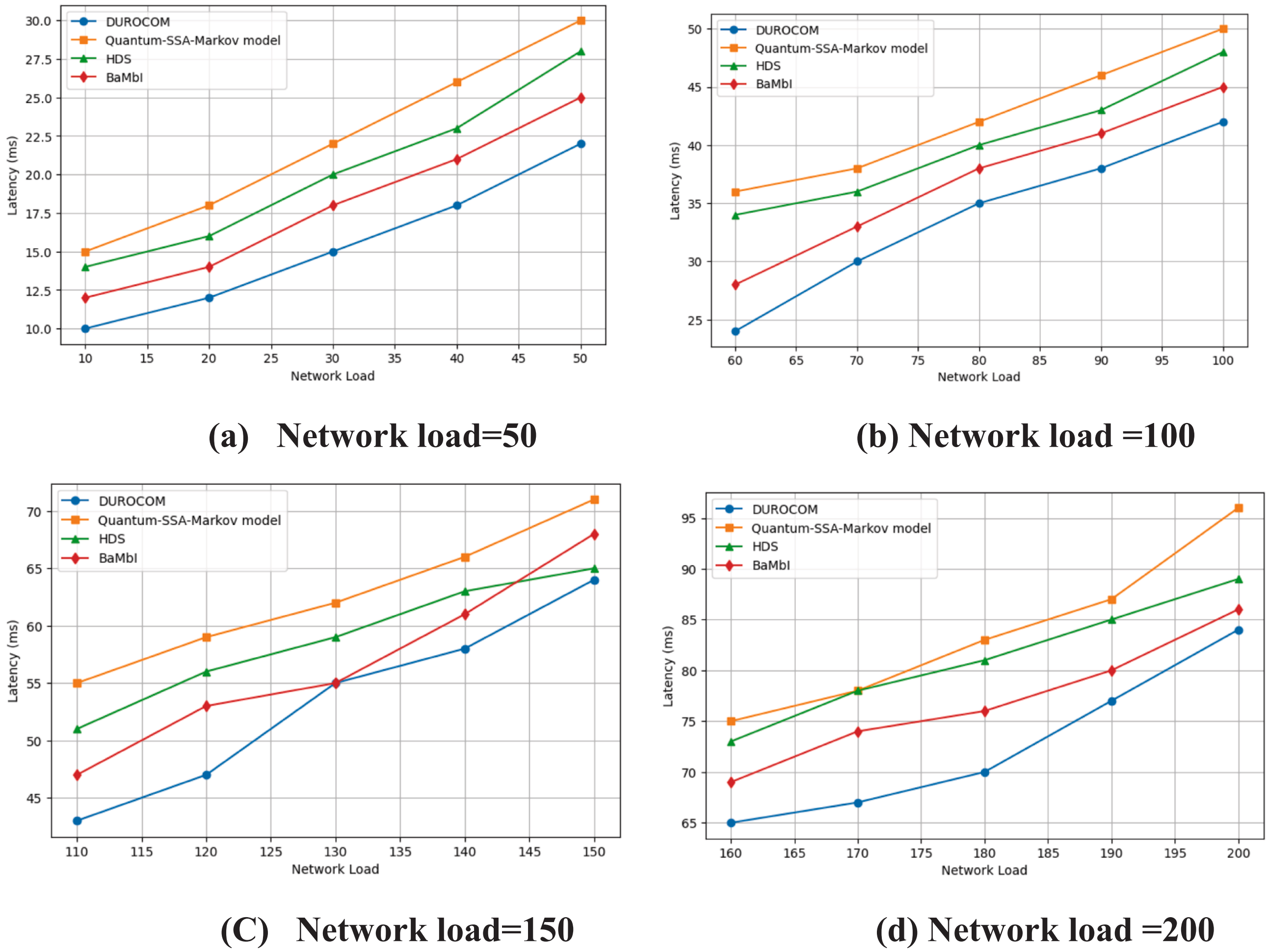

Fig. 9. Latency comparison.

DR and TP. QoS is robustly provided without excessive energy consumption by the combination of weak TP and DR adaptation and quick CI adaptation.

Fig. 7 shows the comparison of initial IoT devices and final energy usage employing communication methods. The starting EC value is shown by the green bar, and the EC following the implementation of optimized communication protocols is shown by the blue bar. By demonstrating the efficiency benefits in the communication processes of

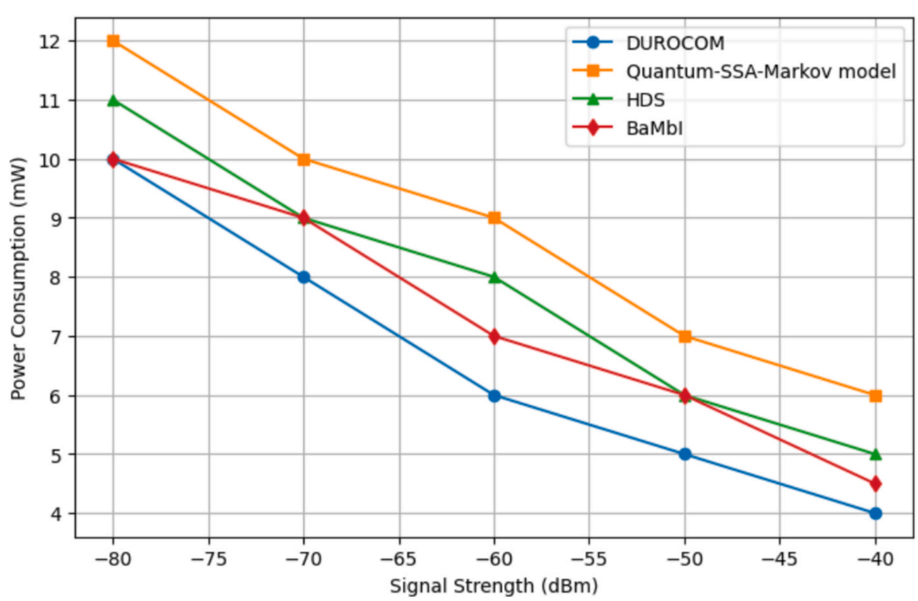

Fig. 10. Adaptive power control effectiveness comparison.

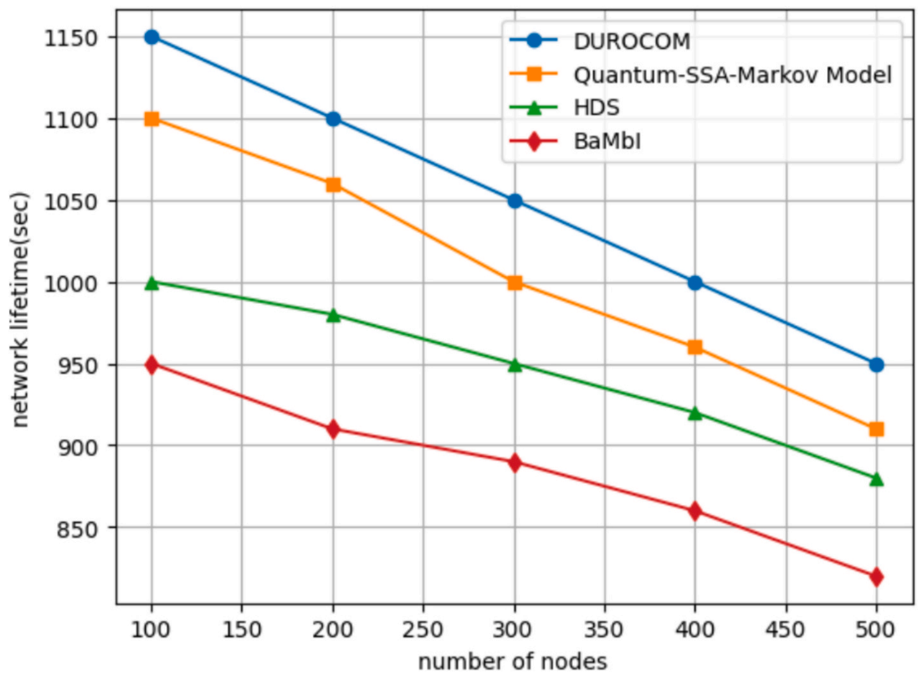

Fig. 11. Network lifespan comparison.

IoT devices, the chart demonstrates the reduction in EC attained through protocol optimization. A system with a lower y-axis value is more energy-efficient, demonstrating the beneficial effect of optimization efforts on total energy usage.

Fig. 8 illustrates the throughput comparison of DUROCOM with three existing techniques: Quantum-SSA-Markov Model, HDS, and BaMbI, as the number of network nodes increases from 10 to 50. The results indicate that DUROCOM consistently achieves the highest throughput across all node configurations, demonstrating its superior efficiency in handling network traffic. In contrast, the Quantum-SSA-Markov Model exhibits the lowest throughput, suggesting a performance limitation in high-node-density scenarios.

HDS and BaMbI perform better than the Quantum-SSA-Markov Model but remain below DUROCOM. These findings highlight DUROCOM's effectiveness in maintaining high data transmission rates, making it a promising framework for improving network efficiency in large-scale deployments.

Fig. 9 presents a comparative analysis of latency performance among DUROCOM, Quantum-SSA-Markov Model, HDS, and BaMbI as the network load increases from 50 to 200. The results indicate that DUROCOM maintains the lowest latency across all load levels, demonstrating its efficiency in reducing transmission delays. In contrast, the Quantum-

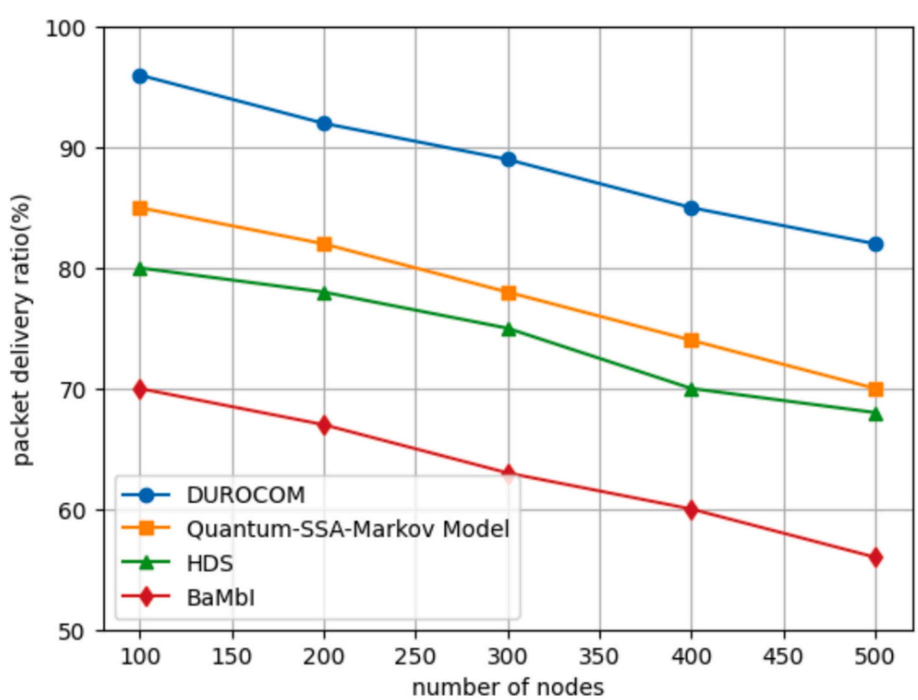

Fig. 12. Packet delivery ratio comparison.

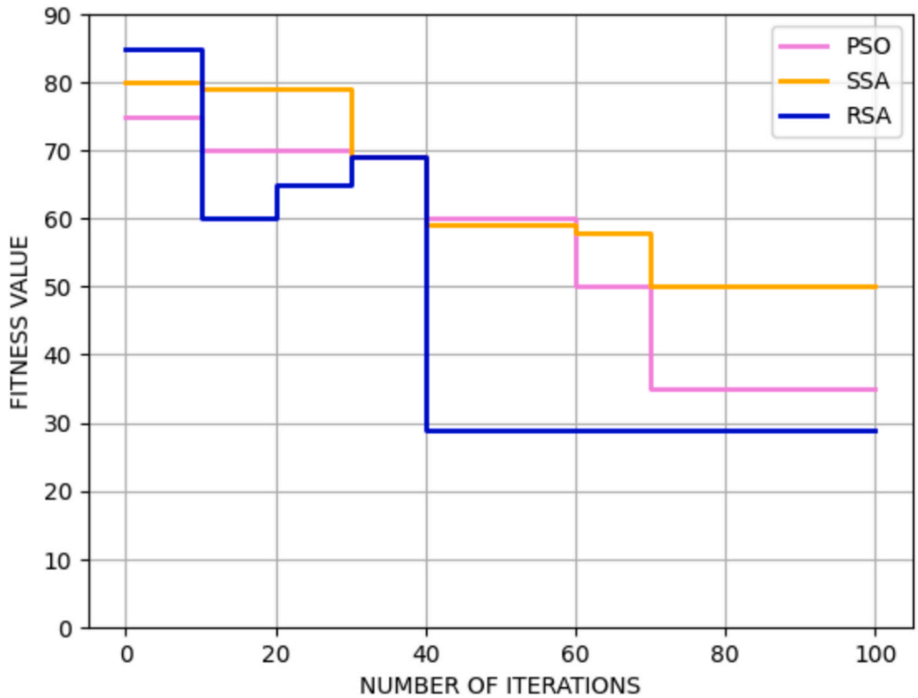

Fig. 13. Convergence analysis of the proposed model.

SSA-Markov Model exhibits the highest latency, suggesting inefficiencies in handling increasing network traffic. HDS and BaMbI show moderate performance, with BaMbI achieving lower latency than HDS but remaining higher than DUROCOM.

Fig. 10 presents a comparative analysis of adaptive power control effectiveness among DUROCOM, the Quantum-SSA-Markov Model, HDS, and BaMbI as the signal strength increases from −80 to −40. The results indicate that DUROCOM maintains the lowest power consumption, demonstrating its efficiency in reducing power consumption. In contrast, the Quantum-SSA-Markov Model exhibits the highest power consumption, suggesting inefficiencies in handling increasing signal strength. HDS and BaMbI show moderate performance, with BaMbI

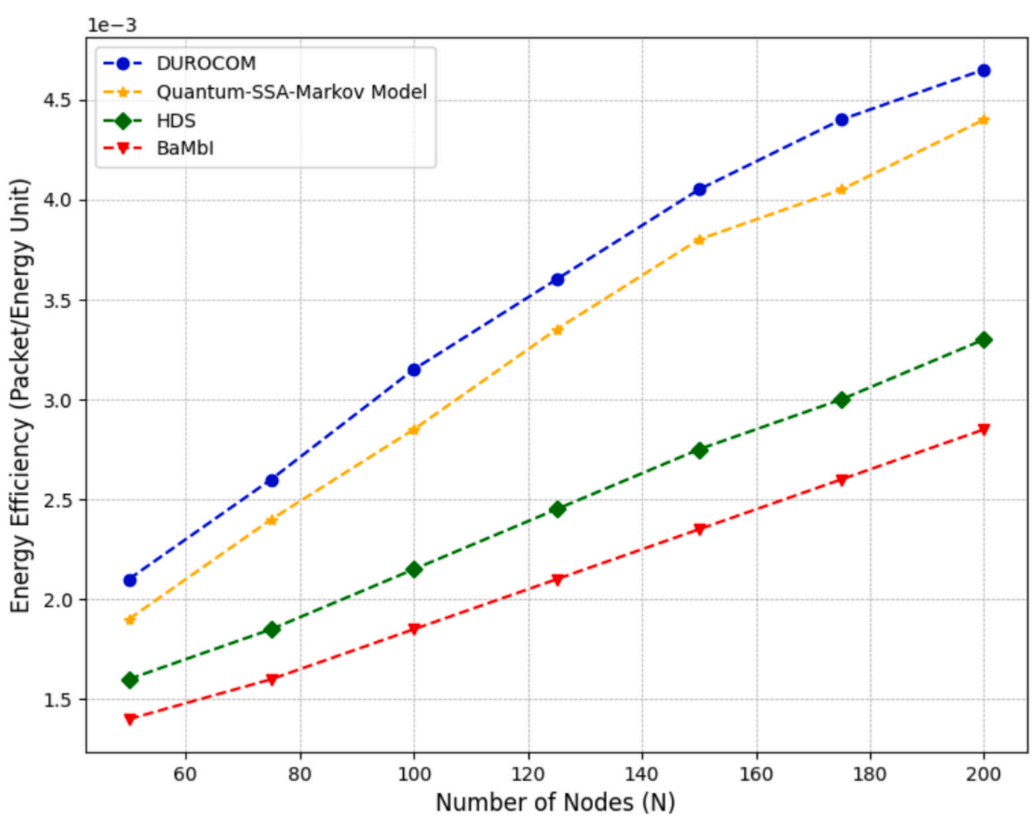

Fig. 14. Energy efficiency comparison.

Table 4
Energy efficiency comparison.

No. of nodes	BaMbI [22]	HDS [24]	Quantum-SSA-Markov Model [27]	DUROCOM [Proposed]
50	1.4	1.6	1.9	2.1
75	1.6	1.85	2.4	2.6
100	1.85	2.15	2.85	3.15
125	2.1	2.45	3.35	3.6
150	2.35	2.75	3.8	4.05
175	2.6	3.0	4.05	4.4
200	2.85	3.3	4.4	4.65

achieving lower power than HDS but remaining higher than DUROCOM.

Fig. 11 shows the efficacy of the suggested DUROCOM approach in terms of NL in comparison to previous studies for different numbers of nodes. Fig. 11 demonstrates that DUROCOM had a longer NL, particularly when there was a significant network load as an average 37 % improvement was achieved when compared to alternative systems. Additionally, the DUROCOM protocol reduced superfluous energy usage and overheads during the data transmission. Additionally, the sensor data was routed to BS using a lightweight, secure routing method provided by DUROCOM.

As depicted in Fig. 12, the developed DUROCOM protocol's

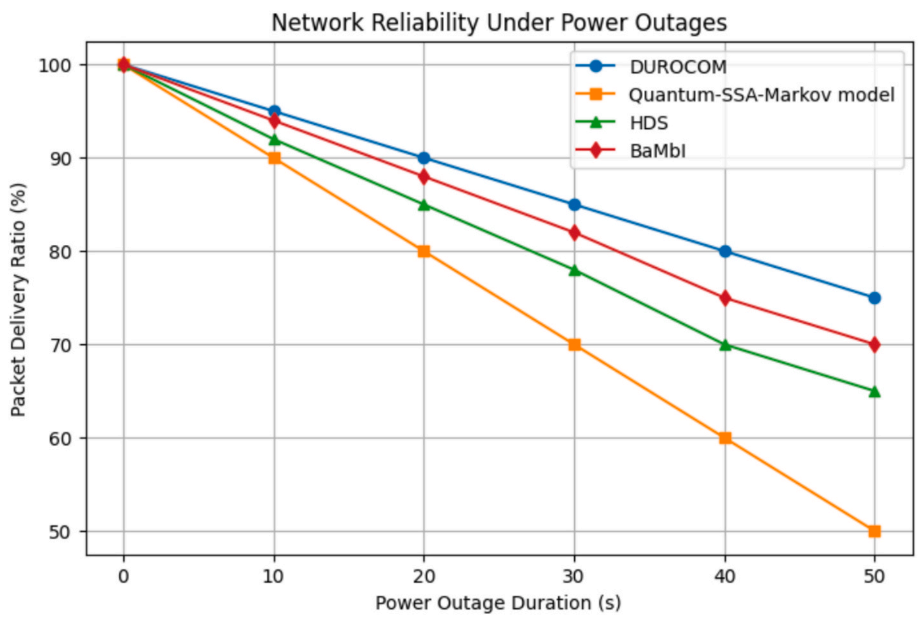

Fig. 15. Network reliability.

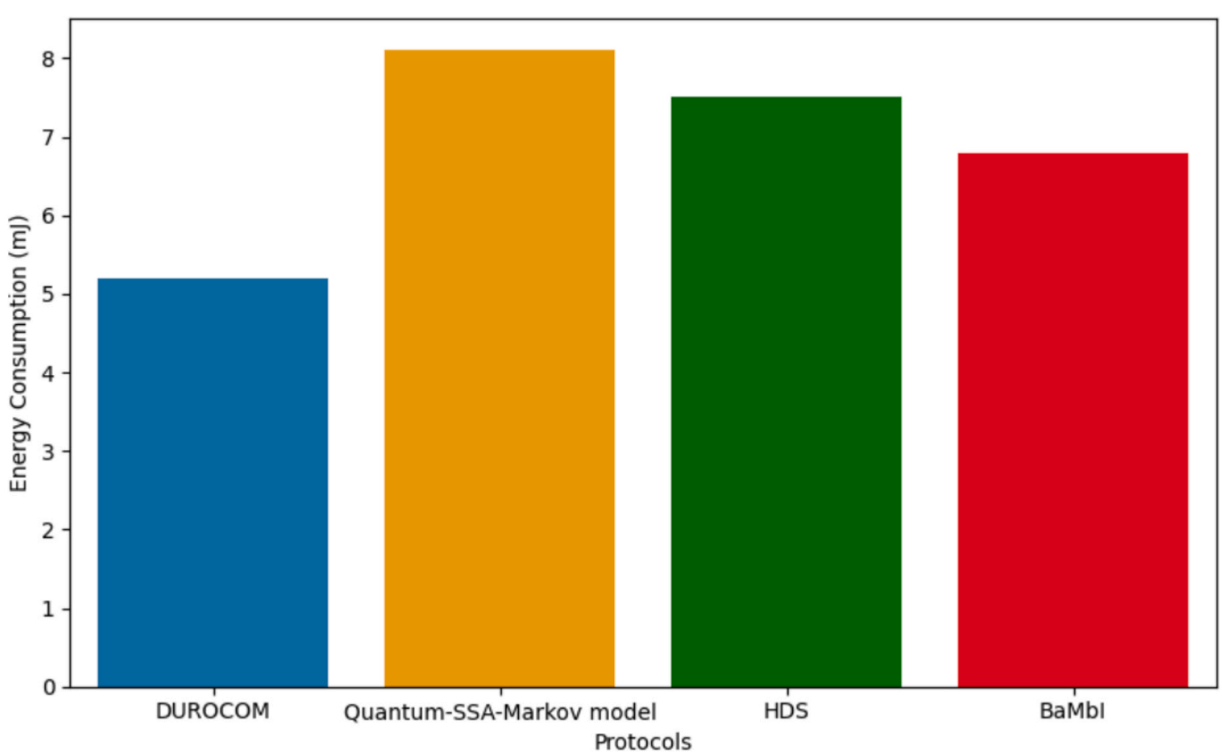

Fig. 16. Energy consumption.

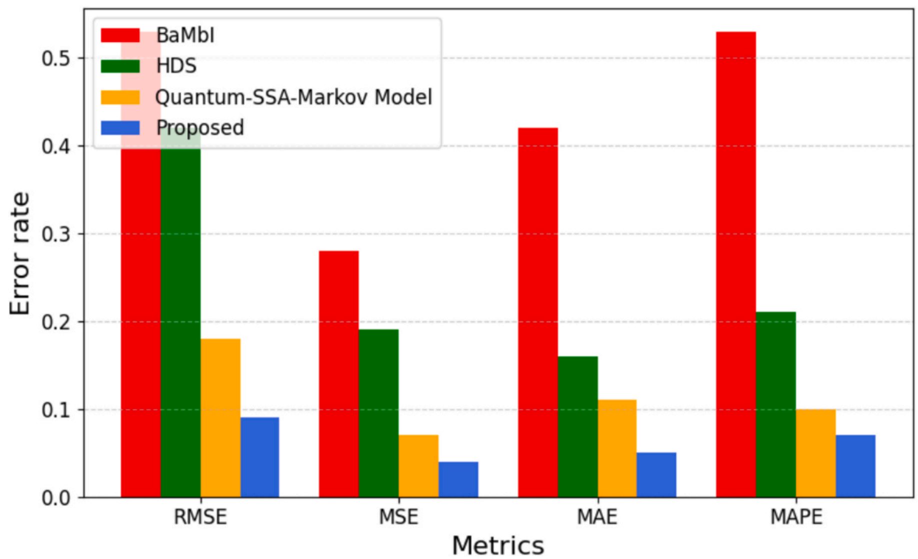

Fig. 17. Error rate comparison.

effectiveness is measured in terms of PDR against the current work under various numbers of nodes. The proposed DUROCOM has demonstrated the highest PDR with an average improvement of 30 % over current systems, particularly in topologies with high node density. Furthermore, the RSA technique was used to strengthen the dependability of the sensor nodes (SNs) that communicated via the BS, which lowers route failures and eventually improves data delivery performance.

Fig. 13 displays the fitness values for the PSO, SSA, and RSA algorithms over time. The y-axis displays fitness value; a lower number signifies more fitness. The proposed RSA method converges the quickest, attaining the lowest fitness value after around 50 rounds. The SSA method converges modestly, whereas the PSO approach converges more slowly but achieves comparable fitness outcomes. This comparison demonstrates that RSA achieves optimal fitness in fewer iterations.

Fig. 14 illustrates many techniques for energy efficiency. As shown in Fig. 14, the DUROCOM technique improves energy efficiency by 7.91 %, 43.57 %, and 66.44 % compared to the Quantum-SSA-Markov Model, HDS, and BaMbI, respectively. This demonstrates DUROCOM's ability to increase network longevity. Fig. 14 shows that energy efficiency increases as the number of SNs also increases. This indicates that there is a direct correlation between these two characteristics. A high network density reduces the distance between nodes, allowing sensor nodes to establish more reliable and efficient paths between one another. This leads to an increase in the network's energy efficiency. Table 4 shows the baseline value of energy efficiency comparison.

Fig. 15 demonstrates the comparison of reliability with the suggested DUROCOM model and existing methods to evaluate the overall reliability of data transmission. The results demonstrate that the DUROCOM model exhibits superior reliability compared to current approaches, indicating a more consistent and robust performance in maintaining data integrity during transmission. Additionally, the analysis shows that the reliability of the system improves, suggesting that the proposed DUROCOM model effectively enhances the resilience and secure data transmission under varying network conditions.

The quantity of energy utilized by the network's sensor nodes is known as energy consumption. As illustrated in Fig. 16, the suggested framework uses less energy than the existing current methods. By placing the node in the center of the network, the observation will minimize the EC, thereby reducing the higher energy costs associated with data communication between sensor nodes located outside of the regions. This demonstrates that our suggested technique is a successful way to reduce the rate of network congestion while improving system effectiveness and energy efficiency.

Table 5
Statistical comparison of the proposed and the existing methods.

Techniques	p-value	Throughput (Mean ± Std, kbps)	Energy efficiency (Mean ± Std)	Latency (Mean ± Std, ms)
BaMbI	0.054	200.4 ± 1.85	2.82 ± 0.05	61.66 ± 1.07
HDS	0.042	210.8 ± 1.72	3.12 ± 0.05	55.64 ± 0.88
Quantum-SSA-Markov Model	0.037	216.4 ± 1.85	3.72 ± 0.05	52.62 ± 0.87
Proposed	0.026	228.4 ± 2.42	4.62 ± 0.03	48.90 ± 0.76

Fig. 17 illustrates the comparison of the error rates of four different techniques. The error metrics evaluated are RMSE, MSE, MAE, and MAPE. Compared to the other models, the suggested DUROCOM shows significantly lower error rates across all metrics, suggesting better performance in terms of communication optimization in IoT networks with limited battery life. This visual comparison shows the developed DUROCOM's capability to enhance network performance while minimizing energy consumption and delay.

Table 5 illustrates a comparative statistical analysis of the proposed DUROCOM protocol against existing models including BaMbI, HDS, and Quantum-SSA-Markov Model. It achieves the highest throughput of 228.4 ± 2.42 kbps, the best energy efficiency at 4.62 ± 0.03, and the lowest latency of 48.90 ± 0.76 ms. Furthermore, the associated p-values confirm the statistical significance of DUROCOM's performance gains, with a p-value of 0.026, which is well below the 0.05 threshold. These results indicate that DUROCOM achieves superior and consistent performance with statistical confidence, validating its effectiveness for real-world smart city applications.

5. Conclusion

In this paper, a novel DUal RadiO COMmunication (DUROCOM) protocol has been designed for battery-constrained IoT networks. The suggested framework achieves energy efficiency and enhances communication reliability through the DSA algorithm. The suggested protocol has been analyzed utilizing a Python simulator. The effectiveness of the developed DUROCOM technique has been examined employing specific metrics including throughput, energy consumption, power control efficiency, NT, PDR, convergence analysis, energy efficiency, network reliability, and latency. According to the comparative analysis, the energy efficiency of the developed DUROCOM framework is increased by 7.91 %, 43.57 %, and 66.44 % as compared to the existing Quantum-SSA-Markov Model, HDS, and BaMbI methods respectively. The proposed framework enhances the communication reliability and energy efficiency but faces challenges like increased protocol complexity and computational cost. This drawback arises due to the integration of the dual-radio architecture and the RSA-based optimization process, which require additional processing and coordination. However, this limitation does not affect the overall quality or effectiveness of the proposed method, as the performance improvements in energy efficiency, latency, and reliability significantly outweigh the computational overhead. Addressing these limitations, the future work will focus on integrating machine learning models for adaptive parameter tuning with a lower computational burden for large-scale deployments in heterogeneous IoT environments.

Ethical approval.

My research guide reviewed and ethically approved this manuscript for publishing in this Journal.

CRediT authorship contribution statement

B. Padmavathi: Investigation, Data curation, Conceptualization. **G. Ramya:** Validation, Supervision, Project administration, Methodology. **M. Shunmugathammal:** Writing – review & editing, Writing – original draft, Validation. **Roopa Muralidhar:** Investigation, Data curation, Conceptualization. **Hab.Eng. Jerzy RyszardSzymański:** Writing – review & editing, Writing – original draft, Project administration, Methodology. **Marta Żurek-Mortka:** Methodology, Data curation, Conceptualization. **Mithileysh Sathiyanarayanan:** Visualization, Validation, Data curation.

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Availability of data and material

Data sharing is not applicable to this article as no new data were created or analyzed in this Research.

Human and Animal Rights: This article does not contain any studies with human or animal subjects performed by any of the authors.

Informed consent: I certify that I have explained the nature and purpose of this study to the above-named individual, and I have discussed the potential benefits of this study participation. The questions the individual had about this study have been answered, and we will always be available to address future questions.

Data Availability Statement: Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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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