

# Autonomous Task Offloading Decision-Making in IIoT Using Digital Twin-Driven Swarm Intelligence Optimization

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## Abstract

The Industrial Internet of Things (IIoT) has revolutionized industries by enabling seamless communication between interconnected devices and systems. However, implementing and operating IIoT systems presents several challenges, particularly in the area of task offloading, where computationally demanding tasks are offloaded to and run on remote cloud servers. To make optimal task offloading decisions, this research suggests combining Digital Twins computer simulations of physical objects with advanced optimization methods. By leveraging the real-time monitoring capabilities of Digital Twins (DT) and the efficiency of the Swarm Intelligence-based Lion-Bat Fusion Algorithm (SI-LBFA), the proposed model seeks to reduce mission execution time while accounting for server capacity, bandwidth constraints, and device power consumption. The SI-LBFA, a hybrid optimization method that combines the Lion-Bat Fusion approaches, is employed to refine offloading performance. The efficiency of the proposed model is demonstrated through simulations conducted using MATLAB, with a comprehensive performance analysis highlighting its effectiveness in improving task offloading decisions within IIoT environments.

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**Keywords:** Industrial Internet of Things (IIoT), Task Offloading, Digital Twins, Swarm Intelligence based Lion-Bat Fusion Algorithm (SI-LBFA).

## 1 Introduction

Real-time data sets and research have been enabled by the IIoT accelerated growth, edge, and cloud computing and fifth-generation (5G) statement. These advancements coupled with the digitization of physical and manufacturing processes can potentially enhance the productivity and efficiency of the systems that have been implemented (Al-Hawawreh & Hossain, 2024). IIoT, the term for the use of IoT technology in industries, offers an encouraging means of autonomously gathering and storing object-level data in real-time across the whole production process (Guo et al., 2021). The completion of the organization response and all data gathered from physical sensors are recorded by the DT. Therefore, DT's primary responsibility is to forecast and analyse the performance of physical system to anticipate malfunctions or faults and to provide data about the system for optimal management (Alshathri et al., 2023). A DT framework is a computer-simulated digital model of a physical system or function, e.g., an industrial system. To accurately depict the actual attributes and behaviors of the physical process or object being represented, DTs are constantly optimizing with real-time information (Sasikumar et al., 2023). The adoption of sustainable manufacturing techniques continues to encounter difficulties and obstacles due to environmental concerns. The adaptability of physical production is the primary focus of traditional smart manufacturing paradigms, which also seek to optimize product production and preservation procedures (Ma et al., 2022). The goal of the research is to design an optimized task offloading model in IIoT contexts with the synergy of Digital Twins and the Swarm Intelligence-based Lion-Bat Fusion Algorithm (SI-LBFA) (Kumar & Rajeshwari, 2024). The proposed methodology aims to minimize the task execution time by considering server capacity, bandwidth, and device power usage (Verma & Nair, 2025).

## 2 Related Work

To improve the quality of service without compromising credibility, researchers have introduced a distinctive framework named FDEI that couples Federated Learning (FL) with DT-enabled IIoT. To enhance modeling efficiency, the researcher designed the FDEI model with FedOA, a dynamic optimization FL algorithm that continuously adjusts the model compression ratio and local update factor in IIoT environments with limited resources (Yang et al., 2024). To facilitate real-time intelligent management of these networks, scientists were developing a DT Network (DTN) for the IIoT that simulates sensors, actuators, and networking infrastructure. The use of Eclipse Hono allows efficient network device communication, and Eclipse Ditto models the device states digitally and provides them with convenient access to the DTN (Kherbache et al., 2022). The framework initially introduces a DT model that makes it easier to make a virtual environment for simulating and reproducing IIoT security-critical operations. Second, researchers suggest a blockchain-based information transfer method that uses smart contracts to guarantee facts' authenticity and integrity (Rajan & Srinivasan, 2025). Lastly, the Intrusion Detection System (IDS) is applied to legitimate information that has been collected from the blockchain by the DL method (Sethuraman, 2023). The suggested Binary Arithmetic Optimization Algorithm based on Variational Recurrent Autoencoder-based Intrusion Detection (BAOA-VRAEID) method targets the convergence of DT and the IIoT server, which gathers industrial transaction data and assists with improving the IIoT environment's security and communication privacy (Kumar et al., 2022; Ahmed & Alnatheer, 2025). The IoT of Gas-insulated Switchgear (GIS) was established using this approach, which is practical. For a better mapping of intricate systems in the digital world, it is

recommended to propose a unified design for IoT systems that can adapt to allow an internal extension of the DT and multi-DT connectivity (Jiang et al., 2021). These constraints were addressed by implementing an expandable and adaptable IIoT-based platform that offers two advantages: first, it facilitates the development of personalized data representations of manufacturing systems and their entities, including people; second, it offers a modular infrastructure with interchangeable parts for simple DT instantiation and ramp-up (Menon & Choudhury, 2025). A platform’s function ability has been made available to the public after being evaluated in a lab environment using various apps. Lastly, possible future uses for the suggested DT are examined, and emphasizing its primary advantages (Montini et al., 2022). Only when required will the DT's processed data be viewed and represented on the cloud. To prevent the frequent transfer of sensitive data, all the data sent during the procedure are consist of result reports (Mohammad & Azam, 2015). According to simulation results, the recommended confirmation technique is faster than the conventional protocol (Naddaf & Anbaran, 2016; Nazarova et al., 2024). Furthermore, the PDQN DRL model is used in the research DT framework for a smart industrial unit, demonstrating improved accuracy, stability, and dependability (Chen et al., 2023).

### 3 Methodology

The methodology starts by initiating the DT framework for creating real-time virtual copies of IIoT devices and edge/cloud servers. The decisions regarding offloading tasks are constructed through designing an optimization problem taking into consideration execution time, server capability, bandwidth, and power limitation. The Swarm Intelligence-based Lion-Bat Fusion Algorithm (SI-LBFA) is implemented for optimizing offloading strategies based on adaptive exploration and exploitation techniques. Optimized decisions are executed in a MATLAB simulation, where execution time, resource usage, and network efficiency are measured. A comparative performance evaluation confirms the proposed model against baseline methods. The outcomes prove the efficacy of Digital Twin-driven optimization in improving IIoT task offloading efficiency. Figure 1 lays out the mechanism of the system.

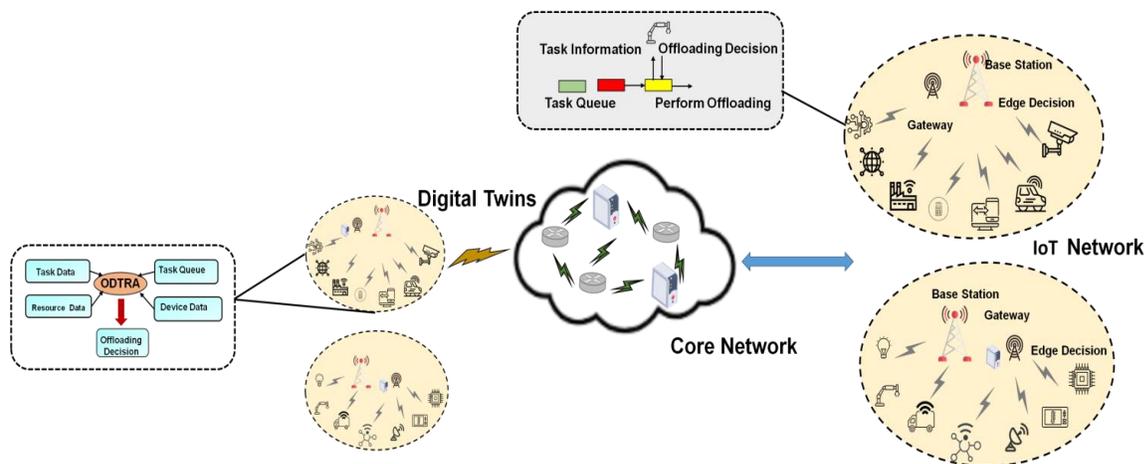


Figure 1: Mechanism of the System

#### 3.1 System Description

The suggested edge-based DT model combines IIoT sensors with edge nodes containing computing servers to process tasks. Devices interact using wired or wireless interfaces without any overlapping

edge node coverage. DTs create virtual replicas, trading data for optimal task execution and resource efficiency. The SI-LBFA supports smart task offloading by using DT capabilities to make dynamic decisions on system state, network, task size, and available resources. To optimize bandwidth utilization and EC, reducing EED and maximizing resource usage. The model guarantees adaptive decision-making through iterative DT parameter updates. Network handovers are controlled by discarding transmitted tasks upon device movement out of coverage. The SI-LBFA-driven model improves real-time industrial applications through enhanced smart offloading, execution efficiency, and resource management.

### **3.2 Communication and Computation**

**Communication:** Each user of the ED is associated with a DT that helps with computation offloading decisions. There is a wireless base station to manage communication among user nodes and the edge computing server. A decision vector captures the offloading decision for every ED, such that a part of the task is offloaded and the other part is processed locally. The rate of transmission is influenced by channel gain, transmission power, interference from neighboring devices, and background noise. The DT maximizes offloading decisions for improving system performance with reduced interference.

**Computation:** The computation model places tasks in terms of CPU cycles and data sizes, with resources managed by EDs and edge servers. Digital Twins provide real-time resource utilization, and the RA system considers availability, schedules, and task-based needs.

### **3.3 Local and Offloading Model**

In local computing, the computation task runs on the local machine with DT support, optimizing computation based on real-time resource information. The execution time takes into account computation capacity and DT processing latency, whereas energy consumption is based on CPU cycles, data size, and transmission efficiency. In the offloading computation strategy in the context of the DT, computations are offloaded from EDs to edge servers through BS, involving overhead in computation time and energy usage. The overall computation time takes into account the transmission of data, computation power, and information from the DT, and energy usage considers transmission and server execution. An optimization model strives to minimize overall computation time and energy usage through optimal offloading choices for each ED user.

### **3.4 Offloading with Digital Twin and Swarm Intelligence based Lion-Bat Fusion Algorithm (SI-LBFA)**

SI-LBFA is to be utilized for intelligent and adaptive offloading of tasks in IIoT scenarios with real-time decision-making based on optimization of execution time, server capacity, bandwidth, and power constraints. The strategy integrates dynamic exploration with the Bat Algorithm (BA) and effective local exploitation with the Lion Algorithm (LA) to encourage task allocation accuracy. Bats utilize echolocation to estimate velocity correction, and distance, and enhance positions, while lions optimize task allocation through territoriality and pride-based mechanisms. Optimizing continuously allows loudness and pulse rates to dynamically adjust in an attempt to trade exploration and exploitation. By incorporating BA's echolocation-based flexibility with LA's territorial optimization, SI-LBFA optimizes global search efficiency and local fine-tuning to maximize autonomous, efficient, and resource-aware task offloading decisions in cloud-edge IIoT networks.

### 3.3.1 Lion Algorithm

LA is a metaheuristic approach in which every node within the network is a lion. Nodes are rated, according to residual energy ratio (RER) and node degree using the fitness function Equation (1).

$$Fitness(Node) = x_1 \times RER + x_2 \times Degree \quad (1)$$

Where  $x_1$  and  $x_2$  are weights ranging from 0 to 1. The RER of a node is expressed in Equation (2).

$$RER(K_j) = \frac{Available\_Energy(K_j)}{Total\_Energy(K_j)} \quad (2)$$

The node degree is computed as Equation (3).

$$Degree(Node(K_j)) = \frac{Number\ of\ Neighbors(K_j)}{Total\ Nodes\ in\ the\ cluster} \quad (3)$$

### 3.3.2 Phase of Hunting

Lions in a pride organize into hunting groups, with the fittest serving as the center wing, and others as left and right wings. The movement of prey is determined by the fitness of hunters, as in Equation (4).

$$Prey_{newpos} = Prey_{oldpos} + rand(0,1) \times PI_{fitness} \times (Prey_{oldpos} - hunter) \quad (4)$$

To encircle the prey, hunters adjust their positions iteratively, Equation (5)

$$Hunter_{oldpos} = rand\left((2 \times Prey_{oldpos} - Hunter_{oldpos}), Prer_{oldpos}\right) \quad (5)$$

This iterative process continues until an optimal offloading decision is reached. If a hunter reaches the prey's position, the best solution for task offloading is selected; otherwise, the process continues until convergence.

### 3.3.3 Bat Algorithm

The approach utilizes the Bat Algorithm to obtain autonomously self-sustaining offloading decision-making in IIoT systems. The method maximizes resource usage depending on execution time, server capacity, bandwidth, and power consumption constraints. Bats utilize echolocation to calculate distance, distinguish between prey and barriers, and adaptively modify flight patterns. Each bat flies randomly with velocity ( $u_j$ ) at a position ( $w_j$ ), with a constant minimum frequency ( $e_{min}$ ) and a variable wavelength ( $\lambda$ ). The frequency, loudness ( $B_j$ ), and pulse rate are adjusted iteratively to enhance the solution quality ( $e_{min}$ ), as elaborated in Equations (6) to (8).

$$e_j = e_{min} + (e_{max} - e_{min})\beta \quad (6)$$

$$u_j^s = u_j^{s-1} + (w_j^s - w_*)e_j \quad (7)$$

$$w_j^s = w_j^{s-1} + u_j^s \quad (8)$$

Where ( $w_j$ ) represents the bat's position in the search space, ( $u_j$ ) denotes velocity, ( $e_j$ ) is the frequency of the pulse, and ( $\beta$ ) is a random number between 0 and 1. The term ( $w_*$ ) represents the best solution found so far. As bats approach the optimal solution, the loudness ( $B_j$ ) decreases while the pulse

rate ( $q_j$ ) increases in Equations (9 and 10). Where  $\alpha$  and  $\gamma$  are algorithm-defined parameters. The optimization process ensures efficient and adaptive task offloading, reducing computational load while improving IIoT performance.

$$B_j^s = \alpha B_j^{s-1} \quad (9)$$

$$q_j^s = q_j^0 [1 - \exp(-\gamma(s - 1))] \quad (10)$$

## 4 Result

This contrast is drawn on the basis of energy consumption, task offloading, and delay performance of SI-LBFA, LO, and BA under the Digital Twin-based IIoT paradigm, referencing the efficacy of SI-LBFA in alleviating computational tasks using minimum resource usage and latency. The efficacy of the model is illustrated via MATLAB simulations, and rigorous performance analysis proves it is capable of optimizing task offloading decisions for IIoT systems.

**Energy consumption:** The suggested SI-LBFA approach minimizes energy consumption (EC) and performs better than baseline algorithms with increasing task count. The energy usage of different task numbers was analyzed for LO, BA, and SI-LBFA in the DT system. For 20 tasks, LO consumed 40 mJ, BA consumed 38 mJ, and SI-LBFA consumed only 5 mJ. With the task number increased to 100, energy usage went up to 45 mJ for LO, 43 mJ for BA, and 13 mJ for SI-LBFA. At 160 tasks, LO and BA expended 48 mJ and 47 mJ, respectively, whereas SI-LBFA expended less at 17 mJ. For 200 tasks, LO expended 50 mJ, BA expended 49 mJ, and SI-LBFA was more effective at 19 mJ, justifying its effectiveness in reducing energy consumption in Digital Twin-based IIoT task offloading. EC efficiency is enhanced by task offloading optimization, extends the life of devices, and decreases charging frequency in IIoT networks. EC is positively correlated with task size and increases with increased computational loads on IIoT devices and edge servers. Figure 2 displayed the energy consumption.

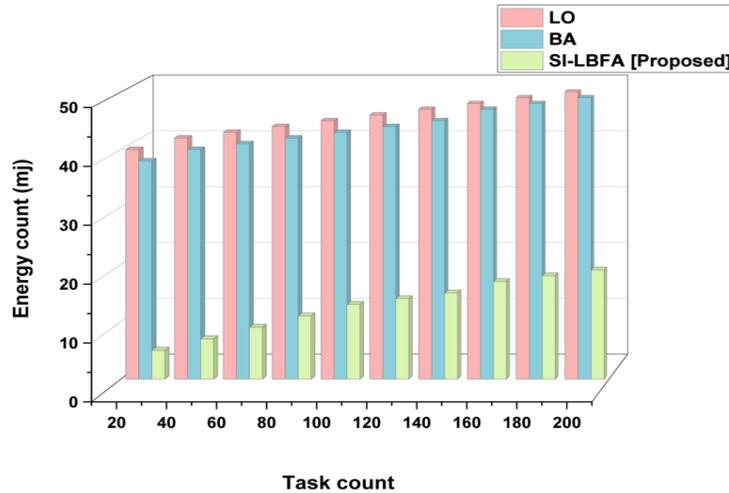


Figure 2: Energy Consumption Analysis

**Task Offloaded:** SI-LBFA is better in task offloading (TO) in the DT scenario. For 20 tasks, LO offloaded 7, BA offloaded 5, and SI-LBFA offloaded 30 tasks successfully. When the number of tasks was 100, SI-LBFA offloaded 38, which was higher than LO 14 and BA 13. When the number of tasks was 160, SI-LBFA offloaded 46 tasks and LO and BA offloaded 18 and 17 tasks, respectively. When the task count was 200 SI-LBFA excelled LO and BA in offloading 49 tasks against them offloading 20

and 19 tasks, respectively and Figure 3 elaborated the task offloaded. The result demonstrates the effectiveness of SI-LBFA in IIoT task offloading optimization by achieving a trade-off between response time, energy, and server usage. The findings confirm that SI-LBFA outperforms conventional techniques in efficiently dealing with computationally intensive loads.

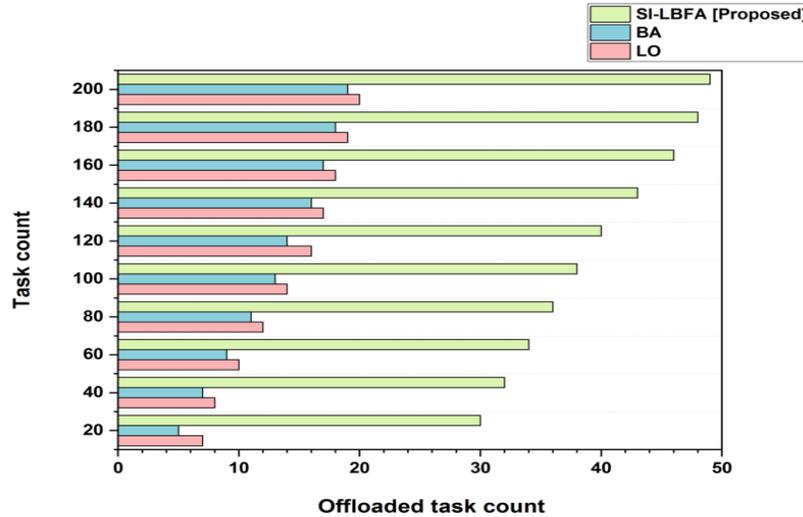


Figure 3: Task Offloaded Testing

**Delay performance:** The delay calculation for different counts of tasks was compared for LO, BA, and SI-LBFA within the DT framework. When 20 tasks were considered, LO measured 32 ms, BA measured 30 ms, whereas SI-LBFA largely minimized delay up to 3 ms. When the number of tasks was raised to 100, LO and BA had delays of 40 ms and 38 ms, while SI-LBFA retained efficiency at only 10 ms. At 160 tasks, LO and BA had delays of 46 ms and 44 ms, while SI-LBFA kept the delay to 16 ms. For 200 tasks, LO recorded the highest delay of 59 ms, BA recorded 48 ms, and SI-LBFA recorded the lowest delay of 20 ms, demonstrating its effectiveness in reducing computational latency. These results validate SI-LBFA's improved performance in reducing delays, optimizing computation latency, and improving the efficiency of IIoT applications, as shown in Figure 4.

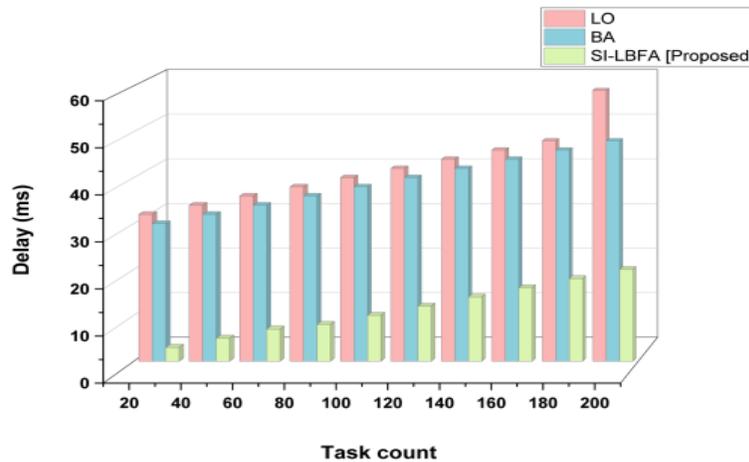


Figure 4: Delay Performance

## 5 Conclusion

The proposed SI-LBFA model optimizes task offloading in the Digital Twin-driven IIoT system by allocating resources effectively, optimizing computations, and saving energy. DT combined with the hybrid Lion-Bat Fusion Algorithm reduces execution time and balances server capacity, bandwidth, and power constraints. Comparative analysis verifies that SI-LBFA performs better than traditional methods in energy efficiency, task offloading, and delay minimization. MATLAB simulations verify its optimization of IIoT task management. Nevertheless, performance is subject to network fluctuation and dynamic workloads. The use of pre-defined parameters also detracts from real-time adaptability. Future research will incorporate edge computing integration to minimize latency further and optimize real-time processing. Adaptive learning methods can enhance dynamic decision-making. Furthermore, scalability in large-scale IIoT networks will be explored to make the approach more universally applicable.

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**Dr.R. Muzhumathi** is currently serving as an Assistant Professor in the Department of Management Sciences at Velammal Engineering College, Chennai, Tamil Nadu. She holds an MBA from Bharathiar University and earned her Ph.D. from Mother Teresa Women’s University. With a decade of experience in academia, she is a dedicated and accomplished educator known for her commitment to teaching excellence, research, and student mentorship. Her academic journey is marked by a strong focus on Human Resource Management, where she has consistently guided students and contributed significantly through scholarly activities. She is UGC-NET and SLET qualified, and has actively participated in various national and international conferences, presenting research papers on contemporary topics. Her contributions to the academic community include published patents and ongoing research aimed at advancing knowledge in her field.



**Abdulaziz Sobirov** is a researcher at Bukhara State Pedagogical Institute, Bukhara, Uzbekistan. His research focuses on the integration of advanced optimization techniques with emerging industrial technologies. he explores how digital twin models and swarm intelligence can be leveraged to enhance decision-making processes in Industrial Internet of Things (IIoT) environments. His work aims to contribute to the development of intelligent, self-optimizing systems that improve operational efficiency, real-time task allocation, and adaptive control in industrial settings.



**Kazim Eshkuvatov**, Candidate of Physical and Mathematical Sciences, is an Associate Professor in the Department of Physics and Mathematics at Gulistan State University, Uzbekistan. His academic expertise lies in applied mathematics, computational modeling, and intelligent systems. Dr. Eshkuvatov's research focuses on the development and application of mathematical algorithms to solve complex problems in data processing, optimization, and control systems. He is actively involved in interdisciplinary studies that integrate mathematical theory with real-world technological solutions, particularly in the context of smart systems and industrial applications.



**Dr.M. Rameshkumar** is a Professor and Head in the Department of Computer Science and Engineering (IoT) at Paavai Engineering College since Sep 2023. He Completed Doctor of Philosophy (Ph.D) in Computer Science & Engineering at Anna University, Chennai. He has got more than 21 years of experience in the field of Teaching & Research and 2 years of experience in Industry. Dr. M. Rameshkumar areas of interest is Networks & Security, Machine Learning, Artificial Intelligence, Data Science and Internet of Things. He acted as a Resource Person for Faculty development programmes, Seminars, Workshops and Guest Lecture Programmes organized by various institutions and he acted as a Syllabus Committee members for Computer Applications Practical Subject in Diploma Students (DOTE). Dr. M. Rameshkumar obtained 4 patent rights for his Technological Innovations. He Participated and Presented Papers in various International/National Conferences and Published more than 30 paper in International Journal. He Received “Best IT Manager” Award from Republic Day Achievers Day 2018 at Anna University Campus, Chennai and Received Bharat Gaurav Ratan Award for Best Department Award from Global Achievers Foundation, New Delhi.