

T-NOTE: Transformer Encoder for Task Offloading in Edge-Fog-Cloud Computing Environments

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Abstract. The abstract should summarize the contents of the paper using at least 70 and at most 150 words. It will be set in 9-point font size and be inset 1.0 cm from the right and left margins. There will be two blank lines before and after the Abstract. . .

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1 Introduction

1.1 Background and motivation

The Internet of Things (IoT) has become a foundational element of modern technology, facilitating the development of innovative applications in domains such as smart cities, healthcare, autonomous systems, and other fields. The proliferation of IoT devices has been rapid and significant, with Cisco reporting a global total exceeding 30 billion [?]. These devices generate a substantial volume of data, approximately 2 exabytes on a daily basis. Achieving maximum potential from these systems necessitates the implementation of efficient processing and analysis methodologies. This requirement presents a formidable challenge in the domains of data management, resource allocation, and system scalability.

The inherent limitations of IoT devices, such as their small batteries, limited processing power, and minimal storage capacity, render them ill-suited to manage the substantial volumes of data they generate. Tasks such as real-time processing of sensor data or computation-intensive applications frequently exceed the capabilities of local devices. Conventional approaches entail the delegation of these tasks to centralized cloud servers. However, network limitations and latency sensitivity frequently render this approach inefficient, particularly for real-time applications [?].

To address these challenges, fog computing has emerged as a distributed computing paradigm that extends the capabilities of cloud computing to the edge of the network. By facilitating the execution of storage, computation, and

data management operations in close proximity to the data source, fog computing contributes to the reduction of latency, power consumption, and network traffic. It is evident that contemporary applications, including but not limited to smart homes, autonomous vehicles, smart agriculture, and healthcare, are contingent on this paradigm to satisfy their real-time and location-aware processing requirements as evoked by [?]. Fog computing, first introduced in 2012, provides a hierarchical architecture that serves to bridge the gap between cloud servers and IoT devices, thereby allowing for seamless data flow and operational efficiency [?].

Despite the advantages inherent in task offloading in fog computing, this process is encumbered by numerous challenges. Optimizing resource utilization, reducing energy consumption, and maintaining Quality of Service (QoS) require robust strategies due to the heterogeneous and dynamic nature of fog networks. Factors such as fluctuating workloads, mobility, and task diversity have been identified as contributing to an increase in the complexity of the situation. To address these challenges, innovative resource allocation techniques are required, including Machine Learning-based (ML) methods, auction models, and heuristic optimization as [?] exhibits.

Conventional resource management techniques frequently employ static heuristic approaches, which prove ineffective when confronted with the diverse and dynamic workloads that are characteristic of fog environments. They exhibit a deficiency in scalability and flexibility, which are prerequisites for real-time task offloading and resource optimization. Consequently, a substantial decline in performance is experienced as system demands increase [?].

To address this problem, metaheuristics such as GA have emerged in the field of offloading as powerful optimization techniques capable of handling the multi-objective nature of fog computing task offloading. GAs excel in exploring complex solution spaces and finding near-optimal trade-offs between conflicting objectives such as latency minimization, energy efficiency, and resource utilization. Unlike traditional optimization methods that often focus on single objectives, multi-objective genetic algorithms can simultaneously optimize multiple performance criteria, making them particularly suitable for fog computing environments where various QoS parameters must be balanced. The evolutionary nature of GAs allows them to adapt to dynamic network conditions and heterogeneous resource availability, providing robust solutions for real-time task offloading decisions.

Recent advancements in the field of Artificial Intelligence (AI), particularly deep reinforcement learning (DRL), have demonstrated considerable potential in addressing the intricacies of task offloading in fog environments. Research has demonstrated the efficacy of AI-driven approaches in reducing latency, energy consumption, and operational costs. As [?] demonstrates in their review, techniques such as centralized Dueling Deep Q-Networks (DDQNs), decentralized learning models, and multi-agent reinforcement learning have been employed to optimize offloading policies and resource allocation. Furthermore, hybrid strate-

gies that integrate artificial intelligence with conventional methods have demonstrated efficacy in heterogeneous fog environments [?].

In order to maintain currency with the latest advancements in this domain, the present study investigates innovative methodologies that integrate the strengths of evolutionary computation and deep reinforcement learning for the purpose of optimizing IoT task offloading. The integration of these approaches addresses the limitations of individual techniques while leveraging their complementary advantages.

1.2 Contributions

To address these gaps, this work makes the following key contributions:

- The proposal of two transformer-based architectures, utilizing DQL for the purpose of task offloading within a cloud-fog-edge environment. The selection of the node (edge, fog or cloud) to execute each incoming task is determined by these models, representing n different actions. The NOTE system is oriented towards node-level features, such as CPU, buffer, and bandwidth. In contrast, the T-NOTE system incorporates additional task attributes, including size, deadline, and CPU-cycle requirements. This capability facilitates a more precise depiction of the interplay between node resources and task demands within a fog environment.
- This work also puts forth a model for offloading in hybrid environments that considers a substantial number of parameters for the QoS. To further expand upon the existing body of knowledge, we implement an adaptation of a scenario with a real dataset within the framework of RayClousSim. We make the scenario and the dataset open-source for the community³. All algorithms used, including NOTE and T-NOTE, are also implemented in this framework.
- Additionally, we conduct a comparative analysis between GAs and a DQL approach. The implementation of these algorithms in the training of an MLP constitutes a pivotal element of the study. The GA approach is employed in a dynamic setting, thereby enabling the MLP to be optimized for multi-objective offloading in real time.

1.3 Paper organization

The remainder of this paper is structured as follows: Section ?? reviews related work; Section ?? describes the problem modeling, including the scenario and QoS modeling; Section ?? details the proposed strategies, from genetics algorithm to deep reinforcement learning approaches, including Transformers-based methods; Section ?? presents the experimental setup and results, as well as a comparative analysis of the proposed methods and that offloading analysis; finally, Section ?? concludes the paper and outlines future research directions.

³ <https://github.com/tutur90/Task-Offloading-Fog>

2 Related Work

Task offloading in Fog/Cloud environments is a relatively recent research area compared to well-studied domains like image classification or time series forecasting. However, the decision-making process for task offloading is inherently complex due to its combinatorial nature.

2.1 Deterministic Approaches

Deterministic algorithms provide a direct method for solving the task offloading problem. For instance, the optimal task assignment algorithm proposed by Yan *et al.* [?] employs a three-step approach: (i) assuming the offloading decisions are pre-determined, (ii) deriving closed-form expressions for optimal offloading, and (iii) implementing bisection search and a one-climb policy. This approach effectively reduces energy consumption and execution time for IoT tasks in Mobile Edge Computing (MEC) systems.

Nevertheless, the task offloading problem is considered NP-hard, as demonstrated by [?, ?, ?]. Consequently, deterministic methods are subject to scalability limitations, prompting the exploration of heuristic, metaheuristic, and AI-based approaches.

2.2 Heuristic and Metaheuristic Methods

Heuristic methods are well-suited for scaling in edge/cloud environments, as they avoid the exponential computational growth of deterministic algorithms [?]. For example, the Deadline and Priority-aware Task Offloading (DPTO) algorithm [?] schedules tasks by prioritizing delays and task priorities, selecting optimal devices to minimize overall offloading time.

Metaheuristic approaches have also been increasingly used for their ability to address the NP-hard nature of task offloading. A recent and comprehensive survey by [?] reviews a wide range of metaheuristic algorithms, including Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), and Grey Wolf Optimizer (GWO)—applied to task offloading in IoT environments. The review identifies key strengths of these methods in balancing latency, energy consumption, and cost efficiency across heterogeneous fog-edge-cloud infrastructures.

Multi-Objective GAs have also proven their worth. [?] introduces the Drafting Niche Pareto Genetic Algorithm (D-NPGA), which optimizes task offloading decisions and improves makespan and cost efficiency for IoT tasks in fog/cloud systems. Multi-Objective GAs are highly efficient at finding a set of Pareto-optimal solutions, allowing decision-makers to select the most appropriate trade-off based on specific requirements.

More sophisticated methods use multiple approaches. For example, Energy-Efficient and Deadline-Aware Task Scheduling in Fog Computing (ETFC) [?] employs a Support Vector Machine (SVM) to predict traffic on fog nodes and

classify them as low- or high-traffic. Then, the method uses reinforcement learning (RL) on the low-traffic group and a non-dominated sorting genetic algorithm III (NSGA-III) on the high-traffic group to make the offloading decision. This allows both algorithms to perform better on adequate tasks.

Despite their strengths, some limitations in scalability and real-time adaptability persist, particularly in highly dynamic environments where task characteristics and network conditions frequently change. This has led to the exploration of AI-based methods, which can learn and adapt to such dynamics more effectively.

2.3 AI Approaches

Machine learning (ML) has recently demonstrated its efficacy in task offloading. For instance, decision tree classifiers [?] determine whether tasks should be offloaded to the fog or cloud, resulting in reduced latency and energy consumption. Logistic regression models [?] have also been applied, estimating the probability of successful offloading by leveraging maximum likelihood estimation.

Deep learning (DL), a subset of ML, deserves special attention due to its dominance across a large subset of AI applications.

Basic deep neural networks (DNNs) have been applied to IoT offloading tasks, such as sarkar_{deep2022}, *where parallel DNNs optimize cost, energy consumption, and latency. However, DRL is making capabilities in dynamic environments.*

For example, [?] utilized DQL to identify optimal offloading policies and resource allocation strategies for user equipment in fog/cloud systems. Their approach combines a dueling deep Q-network for model pre-processing and a distributed deep Q-network for efficient task allocation.

Moreover, multi-agent DRL methods [?] have also been employed to offload IoT tasks. Each IoT device owns a DRL model and trains it to select fog access points, followed by a greedy algorithm to determine cloud offloading. This approach demonstrates competitive performance in energy efficiency compared to exhaustive search and genetic algorithms.

Long Short-Term Memory (LSTM) networks, a type of recurrent neural network, are particularly suitable for the temporal dimensions of task offloading. [?] combined LSTM with DQL to predict task dynamics in real-time, leveraging observed edge network conditions and server load. This hybrid model significantly improved latency, offloading cost, and task throughput.

Transformers, known for their revolutionary impact on natural language processing (NLP), have also been adapted for task offloading. [?] proposed TPTO, a transformer-based framework with Proximal Policy Optimization (PPO). Their model encodes task dependencies using a transformer encoder and employs an actor-critic framework trained with PPO to generate probability distributions for offloading actions, achieving state-of-the-art results in edge computing environments.

While many existing offloading solutions rely on synthetic datasets and focus on Multi-access or Vehicular Edge Computing (MEC/VEC) scenarios [?,?,?], research specifically targeting fog computing remains limited. In particular, models

such as DNNs [?] and DQL [?] have rarely been evaluated in realistic fog environments using real-world data.

Genetic Algorithms (GAs) are often static in nature, such as *bernard_d – npga₂024, pakmehr_ctf_{c2}024, meaningthattheycannotbeemployedinreal-timeapplicationsandcanonlyconverginworldapplicationswheredynamicadaptationisrequired*.

Transformer-based models remain poorly explored in this domain, despite being state-of-the-art in many fields. Some exploration efforts show promise. However, existing approaches often implement basic action spaces, such as TPTO [?], which is designed with only two actions: offloading the task to the cloud or processing it on the edge, not taking into account the resources allocation.

Algorithms are referenced in the Table ?? with the method, the dataset type, the QoS evaluated, and the job type. Used QoS are referenced in the Table ?? with their description.

3 Problem Modeling

3.1 Scenario Modeling

This scenario is modeled according to foundational concepts presented in [?,?,?], following a three-tier offloading approach that involves *edge*, *fog*, and *cloud* nodes. In Figure ??, a high-level cloud-enabled architecture is shown, where a Global Gateway (GG) collects tasks from various IoT devices before determining whether to process them locally or offload them to fog or cloud resources.

The study employs a real-world dataset of IoT-generated tasks to evaluate the performance of the proposed offloading strategies for real applications. The dataset encompasses various tasks collected from IoT devices. Each task is characterized by attributes such as size (in bytes), required CPU cycles, and deadline constraints. This dataset provides a realistic basis for assessing the effectiveness of offloading strategies in handling diverse and dynamic workloads typical of IoT environments.

[width=0.75]figs/cloud_architecture.png

Fig. 1. System Architecture

Architecture Figure ?? presents a schematic overview of the proposed three-tier architecture. The system comprises IoT devices (sensors, mobile nodes, and other edge devices) that generate tasks. These tasks subsequently reach the Global Gateway (GG), which processes them locally if resources are available or offloads them to the fog or cloud layers based on resource availability and energy considerations.

Global Gateway The GG layer is located at the edge and aggregates tasks from local IoT devices. In addition to routing capabilities, the GG possesses limited computational power, enabling it to handle smaller tasks locally and thus reduce network traffic. This approach is particularly advantageous for time-sensitive tasks that can be processed quickly on-site.

Upon receiving a task, several factors are evaluated:

- **Node state:** The current load on each node, including CPU usage, memory availability, and buffer status.
- **Network conditions:** Bandwidth and potential congestion from the GG to fog or cloud nodes.
- **Task requirements** (T-NOTE only): Task size, computational complexity, and deadline or quality of service (QoS) constraints.

Based on these factors, an offloading decision is made to determine the optimal execution strategy for the task. The GG decides whether the task should be processed locally, offloaded to a fog node, or offloaded to a cloud node. Since the three-tier architecture includes multiple fog and cloud nodes, the decision also specifies the particular node to which the task should be sent. This decision-making process is dynamic and adaptive, responding to the current state of the network, available nodes and the task attributes.

Fog Nodes Fog nodes provide moderate computational resources that exceed those of edge devices but remain below the capacity of cloud data centres. These intermediate computing nodes offer reduced latency in comparison to distant cloud nodes, due to their closer physical proximity to the network edge. Fog nodes function as a pivotal intermediate tier for tasks that, whilst not requiring the extensive resources of the cloud infrastructure, cannot be processed locally at the GG. This configuration renders them optimal for applications necessitating balanced performance between computational capability and response time.

Cloud Nodes Cloud nodes represent large-scale data centers with substantial computational and storage capabilities. Although they typically have higher baseline latencies because of greater network distances, they are well suited for computationally intensive applications. Cloud nodes excel in handling large tasks that demand significant CPU and memory resources, making them optimal for complex analytical workloads. They are particularly effective for batch processing scenarios with relaxed real-time constraints, where throughput is prioritized over immediate response. Furthermore, cloud data centers can accommodate high concurrency situations through dynamic resource scaling, allowing them to adapt to varying computational demands efficiently.

3.2 QoS Modeling

Task offloading decisions are evaluated within the RayCloudSim framework developed by [?], a comprehensive simulation platform for modeling and assessing cloud-edge-IoT computing environments based on LEAF [?].

Task Throw Rate In this modelisation, task execution failures can occur due to issues such as *network disconnections*, *node isolation*, or *buffer overflows*.

The *task throw rate* τ is defined as:

$$\tau = \frac{\text{Number of failed tasks}}{\text{Total tasks generated}}. \quad (1)$$

A lower throw rate is indicative of a more robust and efficient offloading strategy.

Latency The latency metric for task offloading is exclusively defined for tasks that achieve successful offloading, as the underlying assumption requires that tasks both arrive at the destination and undergo computational processing. For tasks meeting this criterion, the total latency encompasses three distinct components and is formally expressed as:

$$L_{\text{total}} = L_{\text{transmission}} + L_{\text{processing}} + L_{\text{queuing}} \quad (2)$$

Conversely, for tasks that fail to achieve successful offloading, whether due to transmission failures, processing errors, or other system constraints, the total latency is assigned a null value:

$$L_{\text{total}} = 0 \quad (3)$$

Transmission Delay Transmission delay is composed of transfer delay and propagation delay:

$$L_{\text{transmission}} = L_{\text{transfer}} + L_{\text{propagation}}. \quad (4)$$

1. Transfer Delay: The duration required to send all bits of a packet onto the transmission medium:

$$L_{\text{transfer}} = \frac{S}{B}, \quad (5)$$

where S is the data size (in bits) and B is the allocated bandwidth for the task (in bits per second).

2. Propagation Delay: The time taken for a signal to traverse the medium:

$$L_{\text{propagation}} = \frac{d}{v}, \quad (6)$$

where d is the total transmission distance (in meters) and $v \approx 2 \times 10^8$ m/s in optical fiber.

Processing Delay Processing delay is the time spent by a computing node on executing a task:

$$L_{\text{processing}} = \frac{C \cdot S}{f}, \quad (7)$$

where C is the number of CPU cycles required to process the task, and f is the CPU frequency (in cycles per second).

Queuing Delay Queuing delay captures the waiting time a task experiences when the node is busy executing other tasks:

$$L_{\text{queuing}} = \sum_{i=1}^N L_{\text{processing},i}, \quad (8)$$

where N is the number of tasks that arrived before the current task, and $L_{\text{processing},i}$ is the processing time of each task in the queue.

Energy Consumption Model Similar to the latency metric, energy consumption is exclusively defined for tasks that achieve successful offloading. The simulation framework categorizes energy consumption into three distinct components:

- **Idle Energy** (E_{idle}^i): Energy drawn by node i when it remains idle, estimated through an idle power coefficient P_{idle} .
- **Execution Energy** ($E_{\text{exe}}^{i,k}$): Energy consumed by node i during the execution of task k , based on execution power P_{exe} .
- **Transmission Energy** ($E_{\text{trans}}^{i,k}$): Energy utilized to transmit task k from source node j to destination node i , determined by a per-bit cost $C^{m,n}$ on the communication link.

All energy terms are expressed in Joules (J), while power (P) is measured in Watts (W). Let N denote the number of nodes and T represent the total number of tasks successfully offloaded. The overall energy consumption in the system is calculated as:

$$E_{\text{total}} = \sum_{i=1}^N \left(E_{\text{idle}}^i + \sum_{k=1}^T (E_{\text{exe}}^{i,k} + E_{\text{trans}}^{i,k}) \right) \quad (9)$$

This formulation is intended to ensure that energy consumption measurements reflect only the computational and communication activities associated with successful task offloading. In this way, consistency with the latency metric definition is maintained, and a meaningful performance evaluation is provided.

Node Power Consumption Model Based on the work of [?], the power consumption of a computing node can be approximated by:

$$P(u_{\text{cpu}}) = \alpha + \beta \cdot u_{\text{cpu}}, \quad (10)$$

where:

- α represents the idle power (P_{idle}).
- β is the incremental power coefficient for executing tasks, defined by $\beta = (P_{\text{exe}} - P_{\text{idle}})$.
- $u_{\text{cpu}} \in [0, 1]$ is the CPU utilization ratio.

[?] reported a Standard Error of Estimation (SEE) of 12.9% with this model, indicating a reasonably accurate fit to empirical data.

Idle Energy The idle energy for node i over the entire simulation duration T can be calculated as:

$$E_{\text{idle}}^i = \int_0^T P_{\text{idle}}^i dt = P_{\text{idle}}^i \cdot T. \quad (11)$$

Execution Energy Execution energy can be expressed by integrating the CPU utilization over time:

$$E_{\text{exe}}^i = \int_0^T (P_{\text{exe}}^i - P_{\text{idle}}^i) \cdot u_{\text{cpu}}(t) dt. \quad (12)$$

In practical simulations, full CPU utilization ($u_{\text{cpu}} = 1$) is often assumed while tasks are running, yielding:

$$E_{\text{exe}}^{i,k} = T_{\text{exe}}^{i,k} \cdot (P_{\text{exe}}^i - P_{\text{idle}}^i), \quad (13)$$

where $T_{\text{exe}}^{i,k}$ represents the execution time of task k on node i .

Transmission Energy The transmission energy required to move task k from node j (source) to node i (destination) depends on data size and per-bit link costs:

$$E_{\text{trans}}^{i,k} = s^k \sum_{(m,n) \in I^{j,i}} C^{m,n}, \quad (14)$$

where:

- s^k is the size of task k in bits.
- $C^{m,n}$ is the energy cost per bit (J/bit) on the link from node m to node n .
- $I^{j,i}$ is the set of links used along the path from node j to node i .

This model provide a structured, interpretable framework for quantifying energy consumption in offloading scenarios, thereby facilitating meaningful comparisons of energy efficiency under different scheduling and resource-allocation strategies.

4 Proposed Offloading Strategies

A range of offloading strategies was proposed to explore different decision-making paradigms, including NPGA, NSGA, and DQL. Each approach balances complexity and global optimality to varying degrees.

4.1 Metaheuristics

Metaheuristic algorithms, such as evolutionary methods, excel at exploring large, dynamic search spaces in IoT offloading. Although they have been applied in more static contexts by [?], this work extends them to a *dynamic* genome representation namely, an MLP mapping real-time states to offloading actions, following ideas proposed by [?].

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