A Communication and Computation Converged Framework for Sustainable IoT Applications

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***Abstract*—The Internet of Things (IoT) continues to expand and increasingly integrate into day-to-day life supporting multiple applications ranging from smart homes, and smart cities to autonomous vehicles and healthcare. Developing a sustainable IoT architecture to accommodate advanced applications presents a global challenge. A critical aspect of this challenge is ensuring energy efficiency while supporting a vast array of IoT devices and their service level agreements. A layered IoT architecture, encompassing edge, fog, and cloud layers, offers a viable solution to support these varied IoT applications. By optimally selecting nodes for processing incoming IoT requests from different use cases, energy efficiency can be significantly enhanced. In our research, we have developed frameworks for node selection across the edge-fog-cloud layers using Integer Linear Programming (ILP), and meta-heuristic methods. The frameworks we have implemented ensure not only energy efficiency but also adherence to the network and application-specific Quality of Service (QoS) requirements. The proposed frameworks will be implemented in an event-driven simulation environment to validate their effectiveness in real-time network applications.**

***Index Terms*—IoT, edge, fog, cloud, IoT architecture**

I. Introduction

In today's world, Internet of Things(IoT) is deeply integrated into our daily lives. The surge in IoT applications and use cases, coupled with the exponential growth of IoT devices, significantly intensifies the challenges of energy consumption, an area where resources are already stretched thin. With billions of connected IoT devices from diverse applications such as smart grids, healthcare, autonomous vehicles, and smart cities, each with stringent application and network-specific constraints, addressing the needs of advanced and varied IoT applications in a cost and energy-efficient manner is a significant challenge. For example, smart grids may require latency between 10ms-100sec, while eHealth and autonomous vehicles need latency ranging from 1 microsecond to a few seconds with high bandwidth [1]. Building a IoT architecture tailored to each IoT use case is not viable, given the high costs and inflexibility. Developing an IoT architecture that is capable of accommodating diverse and modern IoT use cases whilst prioritizing energy efficiency is crucial in supporting the sustainable development of IoT applications.

To tackle these challenges, the convergence of communication and computation must be taken into account using three layers of edge-fog-cloud, which would help us achieve the best of all the technologies available [2]. Prior studies have focused on IoT architectures tailored to specific use cases, with a primary emphasis on either computation or communication. These studies often explored energy conservation through load sharing. These studies relied on a singular layer for computation or specific use case, without considering collective requirements [3]. IoT also requires sufficient support for ubiquitous communications, aggregation, and real-time access to services and information. In our work, we considered a layered IoT architecture consisting of cloud, fog, and edge layers, as depicted in Fig. 1. This tri-layer structure offers the flexibility to meet the diverse QoS requirements of various IoT use cases while ensuring prompt processing of incoming IoT requests. The energy efficiency can be achieved by making sure that only the required nodes at each layer of edge-fog-cloud are activated to process the incoming IoT requests. Our research focuses on addressing the challenge of enhancing energy efficiency without compromising the QoS requirements such as latency. We have proposed different approaches including Integer Linear Programming (ILP) models, genetic-based, and latency-hungry-based heuristics for optimal node selection to process diverse IoT requests, with the primary goal of minimizing energy consumption. We evaluated these proposed approaches, focusing on their performance in terms of energy costs and solution time.

II. Proposed Frameworks and Evaluations

The energy consumption of the layered IoT architecture considered in this study (shown in Fig. 1) can be enhanced by optimizing the node selection for processing the IoT request.

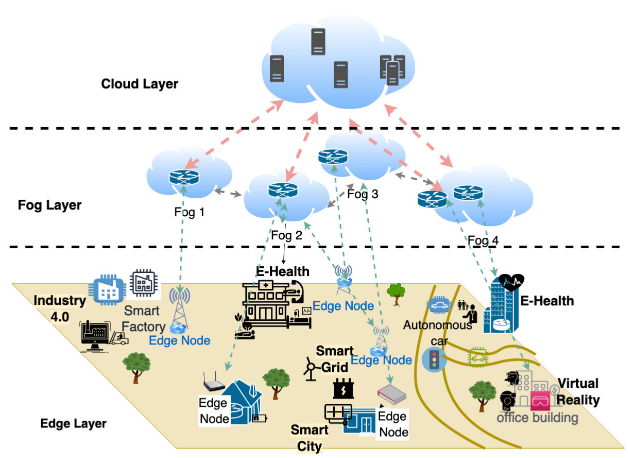

Fig. 1. Layered IoT architecture

This involves choosing an ideal node for IoT request processing that satisfies key application and network requirements like delay, bandwidth, and processing capacity, with various investigated approaches outlined below.

A. Integer Linear Programming Approach

In the initial phase of our research, we applied an optimization framework called Integer Linear Programming (ILP) through IBM CPLEX software for developing and implementing a framework for optimal node selection. The framework, detailed in [4], [5], aims to minimize the energy required for processing IoT requests by using a varying number of nodes across each layer (edge, fog, cloud) of the IoT architecture. Each node at the fog and edge layers is equipped with a custom number of servers, tailored to the specific needs of the IoT architecture. We consider the energy consummation of these activating/using the nodes/ servers in the objective function. The energy costs considered are derived based on the previous research and data available [6].

The framework factors in constraints such as resource capacity, latency, bandwidth, and connectivity to make sure the QoS requirements of the application are satisfied. Validated with IBM CPLEX on a synthetic network dataset, our results demonstrated efficient optimal node allocation for each incoming IoT request, minimizing energy costs while adhering to all application and network-specific QoS requirements.

However, as the network complexity and the number of IoT requests increase, the ILP approach becomes less effective in rapidly processing these requests. Given that ILP is an NP-hard problem, we subsequently proposed meta-heuristic-based approaches for optimal node selection focusing on minimizing energy consumption while achieving a shorter solution time.

B. Meta-Heurisic Approaches

We first introduced a genetic-based approach for optimal node selection, designed to minimize the processing costs of IoT requests. This framework is an extension of the ILP framework previously discussed in [4], [5]. We implemented and evaluated this framework using Python libraries including numpy and deap. Our findings revealed that, while the genetic-based framework processes a large volume of IoT requests faster than the ILP method, the associated processing costs are slightly higher than the suitable values for real-time operations.

Our research then extended to a refined and modified genetic-based approach for selecting optimal nodes in IoT architecture in achieving the same objective with the same constraints. This approach categorizes incoming IoT requests into two groups according to the fog layer's maximum latency supported. Depending on their latency needs, requests are initially routed to either the fog or edge layer. Those unprocessed by the fog layer are redirected to the edge, and if unprocessed there, the cloud layer processes them. Our approach showed reduced processing time compared to the traditional genetic method, with a slight uptick in the total energy cost.

Acknowledging the complexity of implementing meta-heuristic approaches described above in real-world scenarios, we developed another simplified heuristic approach for efficient node selection to balance efficiency and practicality. This approach aligns with the goals and QoS constraints of the ILP framework. We first categorize IoT requests by latency for processing in the appropriate layer and allocate nodes based on the latency requirements. Our evaluations revealed that this approach processes requests faster than the modified genetic framework but with a slight rise in energy cost. All these varied approaches provide insight into achieving an equilibrium between processing and energy efficiencies in IoT architectures without compromising QoS.

C. Implementation in real-world scenarios

In response to the constant influx of IoT requests from diverse IoT applications, our framework needs to dynamically monitor resource availability and provide optimal node selection for processing each request in real time. Therefore, we are developing an event-driven simulation framework, featuring our meta-heuristic node selection approaches. This simulation will mimic the real-time handling of continuous incoming IoT requests and processing them at predefined intervals. The emphasis of the framework is on simulating a specific IoT use case and its different types of IoT requests with varying QoS requirements. These incoming IoT requests would be in real-time and would also follow different incoming patterns and trends. This framework will be used to validate the applicability of the proposals in real-world scenarios.

III. Conclusion and Future Work

This paper provided an overview of our research into optimal node selection approaches to minimize energy consumption in cloud-fog-edge layered IoT architecture. We investigated approaches utilizing ILP and meta-heuristic methods. Our evaluations provided insights into 1) how energy cost can be minimized without compromising the QoS, 2) the applicability of the solution time in real-world implementations.

Future works involve implementing an even-driven simulation to validate the proposals in real-world environments, allowing for a more comprehensive understanding and optimization of achieving sustainable IoT networks and operations.

References

[1] S. Edirisinghe, O. Galagedarage, I. Dias, and C. Ranaweera, "Recent development of emerging indoor wireless networks towards 6g," *Network*, vol. 3, no. 2, pp. 269–297, 2023.

[2] N. Muleta and A. Q. H. Badar, "Study of energy management system and iot integration in smart grid," in *2021 1st International Conference on Power Electronics and Energy (ICPEE)*, 2021, pp. 1–5.

[3] T. Rahman, X. Yao, G. Tao, H. Ning, and Z. Zhou, "Efficient edge nodes reconfiguration and selection for the internet of things," *IEEE Sensors Journal*, vol. 19, no. 12, pp. 4672–4679, 2019.

[4] R. Fereira, C. Ranaweera, J.-G. Schneider, and K. Lee, "Optimal node selection in communication and computation converged iot network," in *2022 IEEE Intl Conf on Parallel and Distributed Processing with Applications*, 2022, pp. 539–547.

[5] R. Fereira, C. Ranaweera, K. Lee, and J.-G. Schneider, "Energy efficient node selection in edge-fog-cloud layered iot architecture," *Sensors*, vol. 23, no. 13, 2023.

[6] I. S. B. M. Isa, T. E. H. El-Gorashi, M. O. I. Musa, and J. M. H. Elmirghani, "Energy efficient fog-based healthcare monitoring infrastructure," *IEEE Access*, vol. 8, pp. 197 828–197 852, 2020.