BENCHMARKING ROUTING ALGORITHMS IN NoC-BASED MPSoCs USING GUARANTEED CONVERGENCE ARITHMETIC OPTIMIZATION WITH ARTIFICIAL NEURAL NETWORKS AND FUZZY MCDM

By

AL-MOLLA YOUSIF R MUHSIN

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BENCHMARKING ROUTING ALGORITHMS IN NoC-BASED MPSoCs USING GUARANTEED CONVERGENCE ARITHMETIC OPTIMIZATION WITH ARTIFICIAL NEURAL NETWORKS AND FUZZY MCDM

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AL-MOLLA YOUSIF R MUHSIN

June 2024

Chairman : Nor Azura binti Husin, PhD
Faculty : Computer Science and Information Technology

Network-on-Chips (NoCs) serve as essential interconnection infrastructures in Multi-processor System-on-Chip (MPSoC) designs, emphasizing flexibility, extensibility, and low power consumption. The effectiveness of communication within NoCs relies heavily on the routing algorithm employed. However, the routing process faces significant challenges, such as deadlock, livelock, congestion, and faults, which impact the Design Space Exploration process. In addition, the selection of appropriate and effective routing algorithms poses a challenge for designers due to multiple criteria, data fluctuations, and the importance of varying criteria.

This study proposed a prediction model-based Artificial Neural Network (ANN) with a Metaheuristic Optimization approach for predicting the utilized routing algorithm by the NoC-based MPSoC platform in order to reduce the time required to specify the NoC-based MPSoC platform configurations. Furthermore, the authors propose a comprehensive assessment of various routing algorithms, aiming to identify the most suitable and effective routing algorithm that satisfies designers' system-level requirements and assessment criteria.

The methodology includes two phases; phase 1 includes developing a prediction model, specifically an ANN optimized using the Guaranteed Convergence Arithmetic Optimization Algorithm (GCAOA-ANN). Whereas phase 2 integrates the fuzzy-weighted zero-inconsistency method and the fuzzy decision-by-opinion score method. The utilisation of the Z-Cloud Rough Numbers environment addresses the challenge of two types of uncertainty.

The study result shows that the phase 1 hybrid GCAOA-ANN model demonstrated superior performance compared to other models. At the same time, a multi-criteria decision-making (MCDM) approach (phase 2) analysis reveals that Adaptive Dimensional Bubble Routing, Message-based Congestion-Aware Routing, and Dynamic and Adaptive Routing Algorithms are ranked as the top three routing algorithms, respectively.

Keyword: Low Power Consumption, Artificial Neural Network, Network-On- Chips, Fuzzy MCDM, Multi-Processor System-On-Chip SDG: Industry, Innovation and Infrastructure

SDG: GOAL 9: Industry, Innovation and Infrastructure

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENANDAARASAN ALGORITMA PERALATAN DALAM MPSoCs BERASASKAN NoC DENGAN PENGOPTIMUMAN ARITHMETIK PERTUBUHAN YANG DIJAMIN DENGAN RANGKAIAN NEURAL TIRUAN DAN MCDM FUZZY

Oleh

AL-MOLLA YOUSIF R MUHSIN

Februari 2024

Pengerusi : Nor Azura binti Husin, PhD
Fakulti : Computer Science and Information Technology

Rangkaian dalam cip (NoCs) berfungsi sebagai infrastruktur perhubungan penting dalam reka bentuk Sistem Dalam Cip Multipemproses (MPSoC), yang mementingkan fleksibiliti, kebolehlanjutan dan penggunaan tenaga yang rendah. Keberkesanan komunikasi dalam NoCs sangat bergantung pada algoritma penghalaan yang digunakan. Walau bagaimanapun, proses penghalaan menghadapi cabaran yang ketara, seperti kebuntuan, gangguan hidup, kesesakan dan ralat, yang memberi kesan kepada proses Pemeriksaan Ruang Reka bentuk. Di samping itu, pemilihan algorithma penghalaan yang sesuai dan berkesan menimbulkan cabaran bagi pereka bentuk, memandangkan banyak kriteria penilaian, turun naik data dan kepentingan kriteria yang berbeza-beza.

Dalam kajian ini, kami mencadangkan ramalan berasaskan model Rangkaian Neural Buatan (ANN) dengan Pendekatan Pengoptimuman Metaheuristik untuk meramalkan algoritma penghalaan yang digunakan oleh NoC bedasarkan platform MPSoC semasa untuk mengurangkan masa yang diperlukan untuk menentukan konfigurasi platform NoC berasakan MPSoC. Tambahan pula, kami mencadangkan penilaian menyeluruh terhadap pelbagai algoritma penghalaan, bertujuan untuk mengenal pasti algoritma penghalaan yang paling sesuai dan berkesan yang memenuhi keperluan peringkat sistem dan kriteria penilaian pereka.

Metodologi kajian ini merangkumi dua fasa. Fasa pertama termasuk membangunkan model ramalan, khususnya ANN yang dioptimumkan menggunakan Algoritma Pengoptimuman Aritmetik Penumpuan Terjamin (GCAOA-ANN). Di samping itu, fasa kedua pula menyepadukan kaedah kabur berpemberat sifar ketaktekalan dan kaedah keputusan fuzi berdasarkan skor pendapat menangani cabaran dua jenis ketidakpastian.

Keputusan kajian menunjukkan bahawa model hibrid GCAOA-ANN menunjukkan prestasi yang lebih baik berbanding model lain. Di samping itu, dalam pendekatan Pembuatan Keputusan Berbilang Kriteria (MCDM) (fasa kedua), terdapat tiga algoritma penghalaan berasingan yang dikenal pasti: Penghalaan Gelembung Dimensi Mudah Suai Adaptive Dimensional Bubble Routing, Penghalaan Mesej Berasaskan Kesedaran Kesesakan, dan Algoritma Penghalaan Mudah Suai dan Dinamik.

Kata kunci: Penggunaan Kuasa Rendah, Rangkaian Neural Buatan, Rangkaian-Dalam-Cip, MCDM Kabur, Sistem-Dalam-Cip Pemproses Berbilang

SDG: MATLAMAT 9: Industri, Inovasi dan Infrastruktur

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All praise and thanks to Almighty Allah, with His blessing giving me the strength and passion, could manage to finish the research until this manuscript completed be compiled.

This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Nor Azura binti Husin, PhD
Senior Lecturer
Faculty of Computer Science and Information Technology
Universiti Putra Malaysia
(Chairman)

Maslina binti Zolkepli, PhD
Senior Lecturer
Faculty of Computer Science and Information Technology
Universiti Putra Malaysia
(Member)

Noridayu binti Manshor, PhD
Senior Lecturer
Faculty of Computer Science and Information Technology
Universiti Putra Malaysia
(Member)

ZALILAH MOHD SHARIFF, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 10 October 2024

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ABBREVIATIONS

A	Alternative
ADBR	Adaptive Dimensional Bubble Routing
AOA	Arithmetic Optimization Algorithm
ANN	Artificial Neural Network
C	Criteria
CATRA	Congestion Aware Trapezoid-based Routing Algorithm
DSE	Design Space Exploration
DM	Decision Matrix
DyAD	Dynamic and Adaptive Routing Algorithm
EDM	Constructing the Expert Decision Matrix
EDXY	Enhanced-Dynamic-XY
FDOSM	Fuzzy Decision-by-Opinion Score Method
FWZIC	Fuzzy-Weighted Zero-Inconsistency
GCAOA	Guaranteed Convergence Arithmetic Optimization Algorithm
GOL	Generalized Opposition Learning
IoT	Internet of Things
Lr	Learning Rate
MAE	Mean Absolute Error
MARE	Mean Absolute Relative Error
MaS	Making-a-Stop
MBE	Mean Bias Error
MCAR	Message-based Congestion-Aware Routing
ML	Machine learning
MPSoC	Multi-processor System-on-Chip

NoC	Network-on-Chips
OE	Odd-Even
PSOGW	Particle Swarm Optimization Grey Wolf
QoS	Quality of Service Support
R^2	R-squared
RMSE	Root Means Squared Error
SEJ	Structured Expert Judgement
SI	Scatter Index
SMA	Slime Mould Algorithm
ZCR-FDOSM	Z-number Cloud Rough number Fuzzy-Weighted Zero-Inconsistency
ZCR-FDOSM-BM	Z-number Cloud Rough number fuzzy decision by opinion score method Bonferroni aggregator
ZCRNs	Z-Cloud Rough Numbers

CHAPTER 1

INTRODUCTION

1.1 Background

This chapter describes the study topic, problem statement, and research objectives. The experimental and technical scope of this study is also described in this chapter. Section 1.2 offers an overview of the elements of the study. Sections 1.3 and 1.4 introduce the problem statement and describe the research questions relevant to the current study. In addition, the research objectives are provided in Section 1.5, while the connection between the study objectives, questions, and the problem is discussed in Section 1.6. Furthermore, Sections 1.7 and 1.8 address the study's overall scope and significance. Section 1.9 describes the thesis's overall organization in short. Finally, Section 1.10 summarises the chapter.

1.2 Research Introduction

Internet of Things (IoT) refers to a network of physical devices embedded with sensors, actuators, and connectivity capabilities that enable them to collect and exchange data over the Internet (Al-Hchaimi et al., 2023). Multi-processor System-on-Chip (MPSoC) plays a significant role in the IoT domain. MPSoCs are powerful integrated circuits that combine multiple processing units, memory, and other system components on a single chip. Figure 1.1 shows the NoC-based MPSoC Platform.

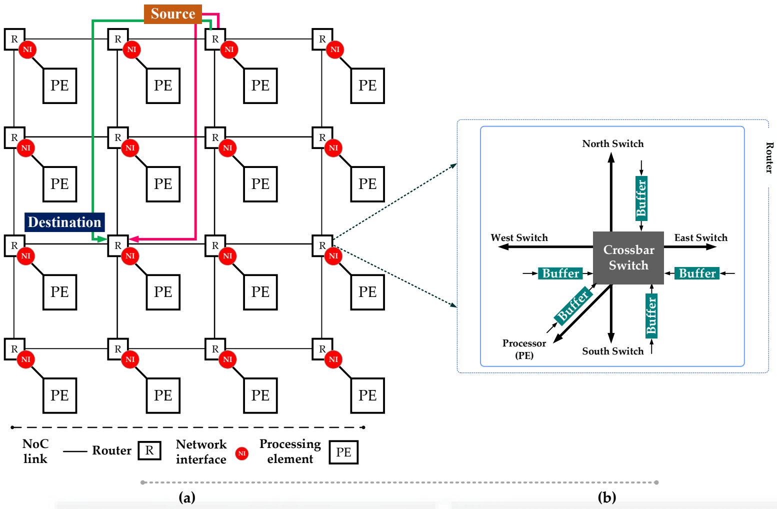

Figure 1.1 : NoC-Based MPSoC Platform

Here are some key roles of MPSoCs in the IoT domain. Processing Power: MPSoCs provide high-performance computing capabilities, allowing IoT devices to handle complex tasks efficiently. Such devices can execute multiple processes in parallel, enabling real-time analytics, data processing, and machine learning algorithms at the edge. System Integration: MPSoCs integrate various components like CPUs, GPUs, DSPs, memory, interfaces, and peripherals into a single chip (Pujol et al., 2023). This integration minimizes the size, power consumption, and cost of IoT devices, making them more suitable for resource-constrained environments.(Loukil, 2023). Real-Time Processing: Many IoT applications require real-time processing, where data needs to be analyzed and responded to within strict time constraints. MPSoCs with dedicated real-time processing units and predictable interconnects can efficiently handle time-sensitive tasks, such as control systems, robotics, and industrial automation. Energy Efficiency: IoT devices are often battery-powered or operate in energy-constrained environments. MPSoCs can be designed to optimize power consumption by incorporating low-power processor cores, power management units, and dynamic voltage and frequency scaling techniques (Nascimento et al., 2023). This enables longer battery life and reduced energy consumption, making them suitable for IoT deployments. MPSoC communication infrastructure is called Network-on-Chips (NoC) (Al-Hchaimi et al., 2022). Figure 1.2 shows the IoT applications.

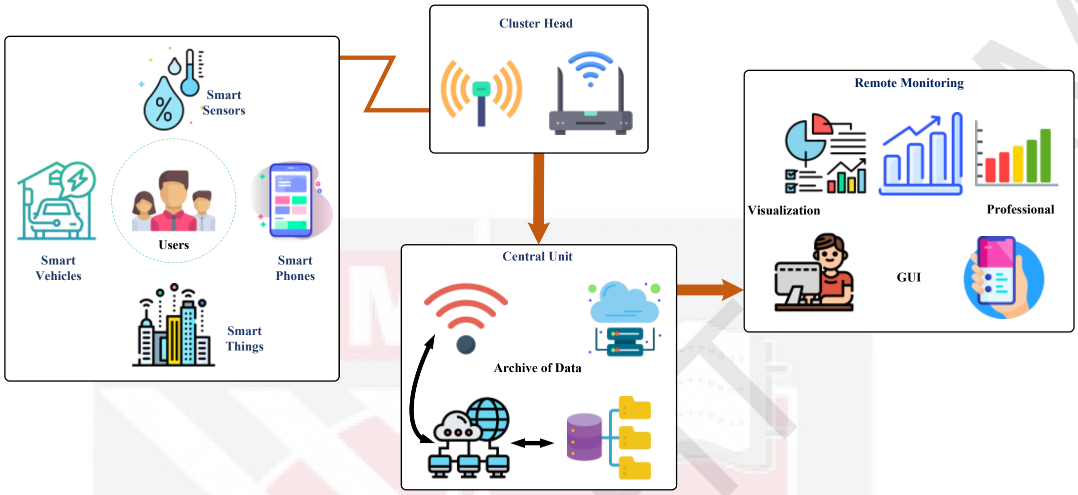

Figure 1.2 : Examples of Using MPSoC in IoT Applications

NoC is the heart of MPSoC. NoC is an expanding technology for the formation of multiprocessor state interconnect patterns. NoC technology is modified to accommodate various multiprocessor needs. NoC gives MPSoC components a way to talk to each other that is reliable, fast, scalable, and uses little power (Rocha et al., 2023; Kumar et al., 2023). NoC is an interconnection design that consists of many processing elements linked to one another by routers and regular-sized wires (links). As seen in Figure 1.2, a processing element may be anything from a microprocessor to an application-specific integrated circuit to a chunk of intellectual property cores that execute a particular program. One of the critical components of NoC-based MPSoCs is the routing algorithm, which is responsible for guiding data packets among routers to ensure timely and reliable communication (Rocha et al., 2023).

The NoC router hosts routing algorithms to find the best path for data transmission between IP cores. Routing algorithms are a set of rules and logical operations performed by routers to determine the shortest path for delivering data packets from source to destination. Through the widespread use of NoC communication systems, routing algorithms have become an essential part)Wang et al., 2017; Soni et al., 2023) (see Figure 1.3). There is a potential competition in routing algorithms design and implementation extended in fields like NoC-based MPSoC performance (R.S. et al., 2022; Okuyama, et al., 2019), security (Al-Hchaimi et al., 2023; Soni et al., 2023), reliability (Seetharaman et al., 2022; Ikechukwu, et al., 2019), and adaptivity (Albahri et al., 2023; Kao et al., 2019; Manzoor et al., 2022). Routing algorithms control the majority of task mapping and resource sharing in the context of NoC-based MPSoC services (Cai et al., 2020). Routing algorithms play a critical role in the design and performance of NoC architectures. NoCs have emerged as efficient and scalable interconnection frameworks for MPSoCs. However, designing an optimal routing algorithm has become a formidable challenge for system designers and engineers in the IoT domain (Kumar et al., 2023). The first challenge arises from the diversity of available routing algorithms. A plethora of algorithms have been proposed to tackle various aspects of communication, including traffic congestion, deadlock prevention, and livelock mitigation (Gaffour et al., 2023; Javed et al., 2020b). Despite these efforts, no single routing technique has emerged as a universally superior solution. Consequently, selecting the most suitable routing algorithm has become a non-trivial task, and designers often struggle to strike the right balance between performance, efficiency, and adaptability (Ali et al., 2023). To address this challenge, researchers have turned to machine learning (ML) techniques as a promising approach to predicting the most appropriate routing algorithm for a given scenario (R.S. et al., 2022). Figure 1.3. shows the role of NoC-based MPSoC.

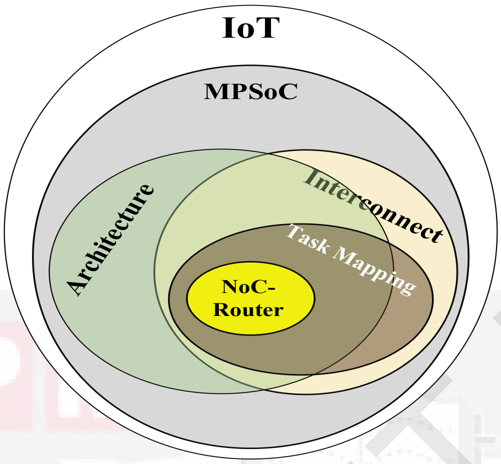

Figure 1.3 : Role of NoC-Based MPSoC in IoT

ML models offer numerous advantages, such as improved performance prediction, reduced latency, energy efficiency, and scalability. Leveraging these models enables real-time or near-real-time decision-making when selecting the routing algorithm for incoming communication requests. ML enables the comparison of mesh and ML-mesh topologies, revealing that the latter yields 75% lesser FPGA resource utilization and 33.2% lower network latency under localized traffic (Parane et al., 2020). Another author (Bhowmik et al., 2021) employed ML to enable quick and accurate evaluation of various performance metrics, which is crucial for efficient architectural design. This approach contrasts with traditional NoC simulators that tend to be slow, particularly with varying architectural sizes. The proposed Linear Regression framework achieves impressive results, with up to 94% accuracy and a remarkable speedup of up to 2228×, providing valuable insights into network latency, hop count, maximum switch, and channel power consumption for varying mesh NoC parameters (Bhowmik et al., 2021). Moreover, simulations with real-world benchmarks demonstrate that the

Reinforcement Learning-based approach outperforms non-ML-based solutions, achieving a 30% reduction in the energy-delay product and a 50% improvement in throughput. This advancement is crucial in adapting NoC designs to the changing demands of heterogeneous components, optimizing performance, and energy consumption in modern multiprocessor systems-on-chip (Reza, 2020). NoC-based MPSoC platforms can achieve enhanced performance and adaptability, which is crucial for meeting the dynamic demands of IoT applications (Jallouli et al., 2022). Despite the strenuous efforts of previous studies to investigate MPSoC issues, the matter of assisting designers and engineers of NoC-based MPSoC platforms in predicting and evaluating routing algorithms has rarely been reported. Current literature on the prediction and evaluation of routing algorithms of NoC-based MPSoC is sparse. A few studies have discussed the ML prediction of NoC performance based on the communication channel's throughput and latency. However, they are limited to one aspect of performance evaluation while neglecting the other aspects, such as throughput and power dissipation (Bhowmik et al., 2021; Parane et al., 2020; Reza, 2020).

However, the successful implementation of ML-based prediction raises other challenges. Firstly, the difficulty lies in effectively selecting the ML algorithms in order to ascertain the most appropriate one for a specific undertaking. Whereas the excellent outcomes obtained by ML implementation are attractive, the level of complexity arises from a variety of algorithms. The ability to effectively choose a perfect algorithm and optimize its effectiveness is key to achieving the full promise of ML and guaranteeing successful and significant outcomes (Ibrahim et al., 2022a). Secondly, evaluating the design and performance of the predicted routing algorithms effectively. The traditional evaluation process often involves comparing individual routing techniques based on isolated criteria, overlooking the interplay of trade-offs and conflicts that exist among different evaluation metrics (Balakrishnan et al., 2023). Design and performance metrics (Chen et al., 2022) of each routing algorithm are the criteria (size, topology, routing type, routing characteristics, packet flit size) and (power dissipation, packet injection rate, number of bits, latency, and throughput). Multi-criteria decision-making (MCDM) is one of the most popular techniques for solving evaluation problems and choosing the best routing algorithms.

MCDM is one of the most used approaches in expert systems and decision science domains to solve multi-criteria decision problems, particularly concerned with making a suitable decision based on the available data (Alsalem et al., 2021; Palanikumar et al., 2023; Uwe et al., 2022; Zaidan et al., 2023). The procedure for assessing and choosing the most suitable table routing algorithms with the MCDM method includes several significant steps. The first step is to determine the essential factors for choosing the most suitable routing algorithms. The second step is assigning weights to every factor based on its perceived importance. In the third step, evaluate the routing algorithms at hand against the relevant factors using an MCDM method; after the evaluation, determine the rank scores for every routing algorithm (Rashid et al., 2019; Alnoor et al., 2022; Liang et al., 2020; Qahtan et al., 2022). The last step, choosing the most suitable routing algorithms, becomes easy by comparing the weighted scores of every routing algorithm.

To the best of our knowledge, previous studies have mainly attempted to propose an integrated hybrid approach for predicting and evaluating the utilized routing algorithms in the NoC-based MPSoC platform using ML techniques and MCDM methods. Two major criteria, namely, design and performance, are commonly used to evaluate the routing algorithms in the NoC-based MPSoC domain. The design contains a set of sub-criteria: size, topology, routing type, routing characteristics, and packet flit size (Gaffour et al., 2023; Shahane et al., 2022). In addition, the routing algorithm's performance has the sub-criteria: power dissipation, packet injection rate, number of bits, latency, and throughput (Akbar et al., 2020; Bahman et al., 2020). For instance, researchers highlighted the significance of congestion-aware routing algorithms in improving NoC performance and power consumption where the proposed two-phase approach, combined with turn restriction and virtual channels, proves to be effective in achieving better network performance and reduced average delays, making it a valuable contribution to the field of NoC design and optimization (Bahman et al., 2020). Therefore, the comprehensive MCDM approach of evaluation covers all the design and performance criteria, and sub-criteria should be developed. This integrated methodology will serve as an approach to support the decisions of the designers of MPSoCs platforms in predicting and evaluating alternative routing algorithms to determine the most efficient one. Moreover, the common thread that binds these two phases is the overarching goal of enhancing the performance of NoC-based MPSoCs. Phase 1 addresses the prediction of NoC throughput based on the routing algorithms that represent the design and performance metrics in the next phase, an evaluation and ranking based on MCDM methods. In contrast, Phase 2 focuses on addressing the optimal routing algorithm in NoC-based MPSoC. This thesis aims to contribute to these complex computing systems' overall performance and robustness by addressing these two aspects.

1.3 Research Problem

The designers and system engineers of NoC-based MPSoC in the network routers have faced difficulty in predicting and evaluating the performance of the utilized routing algorithm to route the data packets among routers of NoC and prevent different traffic congestion, deadlock, and livelock issues, especially because no single routing technique is superior to the rest (Amin et al., 2023; Nguyen et al., 2019). On the one hand, predicting the utilized routing algorithm in a NoC-based MPSoC platform by using ML techniques can offer several advantages such as improved performance, reduced latency, energy efficiency and lower design complexity, scalability, and fast decision making, where the ML models can make predictions quickly, allowing for real-time or near-real-time decision making when selecting the appropriate routing algorithm for incoming communication requests (Rizk et al., 2022).

MPSoC design optimization through routing techniques used in NoC architecture is critical for the best performance. The challenge is that there are no datasets that are accurate representations of what takes place in MPSoC communication (Gomatheeshwari et al., 2023; Ji et al., 2023), so creating a benchmark dataset that would cover both diverse applications, patterns, workload heterogeneity, and scalability in order to predict utilized routing algorithm in NoC-based MPSoC is needed (Chen et al., 2020). A wide variety of ML models have been used to predict in the MPSoC field. Artificial neural network (ANN) is one of the most popular models used to predict in many fields (Choudhary et al., 2023; Joshi et al., 2022; Zhou et al., 2022). However, there are some drawbacks of ANNs that you should be aware of (Khatir et al., 2021; G. Liang et al., 2021). ANNs require a lot of hyperparameters to be set, such as the number of layers, the number of nodes in each layer, the learning rate, and the activation function (AbdulKareem, 2022; Ibrahim et al., 2022a). The complex interaction of these hyperparameters has a direct influence on the learning capacity of the network and its predictive power. Moreover, properly configuring these hyperparameters is a very critical and difficult task, as it needs to be tender enough to prevent overfitting or underfitting (Khatir et al., 2021; Liang et al., 2021). Fundamentally, the wise choice as well as adaptation of hyperparameters allow ANNs to exploit their complex structure potential and thereby improve their predictive accuracy and efficiency in different applications (Ibrahim et al., 2022a; Joshi et al., 2022). MPSoC designers have difficulty selecting the best algorithm to use due to the diversity among available routing algorithms.

The evaluation procedure is an important phase in comparing routing algorithms' performance under similar conditions and utilizing criteria to assess the performance of the routing algorithm. Also, there are rarely studies that have been reported regarding the evaluation and selection of the most suitable routing algorithm. Determining the best and worst routing algorithms helps designers and academics select the appropriate routing algorithm in the MPSoC-based IoT domain that helps solve design space exploration (DSE) issues such as design scalability, variety, and reliability.

For the purpose of shedding light on the specific problems related to routing algorithm selection, four issues are highlighted: (**i**) multiple criteria: Decision-makers face problems in various real-world situations that entail multiple criteria. They face challenges in achieving a collective agreement or assigning precedence to specific criteria. (**ii**) criterion importance: the evaluation of routing algorithms involves a set of criteria, and each criterion's importance varies according to the objectives for which the model is developed. The importance of one evaluation criterion may be increased in exchange for the low importance of another, (**iii**) the trade-off and conflict: design and performance should be measured to evaluate routing algorithms. However, the comparison approach for the previous models in all reviewed studies disregards all evaluation criteria; it focuses on one aspect of the evaluation and ignores the rest because it is not flexible enough to address the conflict or trade-off among various criteria and sub-criteria such as (size, topology, routing type, routing characteristics, packet flit size) and (power dissipation, packet injection rate, number of bits, latency, and throughput) as a sub-criterion respectively (Chen et al., 2020; Choudhary et al., 2023; Gamatié et al., 2019; Jagadheesh et al., 2022), and (**iv**) ambiguity and uncertainty among the criteria the measurement becomes more difficult due to the ambiguity and uncertainty associated with human characteristics (Božanić et al., 2021; Riaz et al., 2022; Zaidan et al., 2023). To address MCDM problems under uncertainty, Bellman and Zadeh introduced the concept of fuzzy sets (Bellman & Zadeh, 1970). Preference evaluations of design alternatives very often involve two groups of uncertainties (Lou et al., 2020): (1) The interpersonal judgmental interaction caused by multiple people's subjective opinions according to their own background, knowledge, expertise, and insight, and (2) the intrapersonal preference vagueness originated from individual expert's fuzzy and inaccurate cognitive structures. As in prior studies, the fuzzy decision by opinion score method (FDOSM) and fuzzy-weighted zero-inconsistency (FWZIC) have been recommended as efficient MCDM evaluation methods proposed for cloud computing and computer networks. Integrating FDOSM and FWZIC methods can help make rational decisions based on the experience of specialists (Albahri et al., 2022; Baqer et al., 2022). FDOSM's key aspect is to identify the best solution by employing the ideal solution concept and the opinion matrix to address actual issues in MCDM (i.e., time consumption, inconsistency, and understandable comparisons) (Alamoodi et al., 2022). FWZIC was introduced by (Mohammed et al., 2022), which is used to identify the essential criteria weights without any inconsistency.

Although FDOSM and FWZIC algorithms are considered the last advanced algorithms in the field of MCDM, the issue of extending MCDM methods to an advanced fuzzy environment, such as Z- Cloud Rough number (ZCR number), is regarded as a critical issue to address the problem of ambiguity, uncertainty, and accuracy. Sadly, previous research seldom takes into account both kinds of uncertainty. Figure 1.4 illustrates the problem statement configuration.

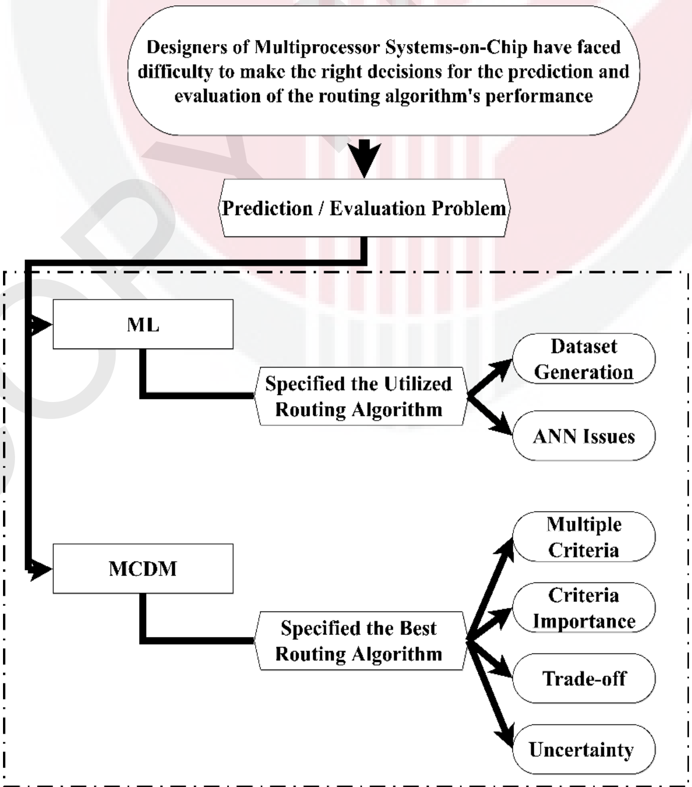

Figure 1.4 : Problem Statement Configuration

1.4 Research Questions

1) What are the available techniques and methods to predict and evaluate routing algorithms in NoC-based MPSoC platforms?

2) What are the requirements needed for prediction and evaluation methodology for routing algorithms in NoC-based MPSoC?

3) Is there any integrated methodology to generate a dataset?

4) What are the optimal optimizer and machine learning algorithms?

5) What are the criteria that have been used to evaluate the routing algorithms in NoC-based MPSoC?

6) What are the suitable techniques for evaluating criteria and ranking alternatives?

1.5 Research Objectives

This study aims to develop a benchmarking methodology for routing algorithms using multicriteria decision-making methods. The objectives of this research are outlined as follows:

To investigate the existing design exploration processes in the context of NoC-based MPSoC platforms and employ routing algorithms and techniques.

1. To identify the metrics of routing algorithms performance and generate a dataset.

2. To develop a prediction model based on ML techniques by integrating the GCAOA with ANN.

3. To construct a decision matrix in order to identify multi-evaluation criteria.

4. To extend FWZIC and FDOSM into a new fuzzy environment (i.e., FWZIC with ZCR number) for weighting criteria and ranking the alternatives.

1.6 The Interaction of Study Objectives, Research Questions, and Research Problems

The research objectives give insight into the questions posed by the research questions, which in turn guide the investigation. Table 1.1 consists of the research questions and their solutions according to their respective aims, and it specifies which aspects of the study issue will be resolved by accomplishing each goal.

Table 1.1 : The Connectivity amongst Research Objectives, Questions, and Research Problem

<table>
<tr><th></th><th></th><th colspan="2">Research problem mapping</th></tr>
<tr><th>Research Questions</th><th>Research Objectives</th><th>Specific Problem</th><th>General problem</th></tr>
<tr><td>What are the available techniques and methods to predict and evaluate routing algorithms in NoC-based MPSoC platforms?</td><td rowspan="2">To investigate the existing design exploration processes in the context of NoC-based MPSoC platforms and employ routing algorithms and techniques.</td><td></td><td rowspan="4">Selection and prediction (Benchmarking)</td></tr>
<tr><td>What are the requirements needed for prediction and evaluation methodology for routing algorithms in NoC-based MPSoC?</td><td></td></tr>
<tr><td>Is there any integrated methodology to generate a dataset?</td><td>To identify the metrics of routing algorithms performance and generate a dataset.</td><td>Generate the dataset</td></tr>
<tr><td>What are the optimal optimizer and machine learning algorithms?</td><td>To integrate the GC-AOA with ANN</td><td>Hyperparameters of ANN</td></tr>
</table>

Table 1.1 : Continued

What are the criteria that have been used to evaluate the routing algorithms in NoC-based MPSoC?	To identify the core metrics that routing algorithms are based on in the context of NoC-based MPSoC.	-Multi Evaluation criteria. -There is a lack of definition of the NoC-based MPSoC evaluation criteria.	
What are the suitable techniques for evaluating criteria and ranking alternatives?	To extend FWZIC and FDOSM into a new fuzzy environment (i.e., FWZIC with ZCR number) for weighting criteria and ranking the alternatives.	The interpersonal and intrapersonal uncertainty Weighting criteria. Ranking routing algorithms - Importance of criteria. - Conflict and trade-off criteria.	

1.7 Scope of the Study

The scope of this study is to explore and improve the methods for assessing the effectiveness of routing algorithms by developing an intelligence module. Therefore, this study aims to develop a prediction module based on a metaheuristic algorithm with ANN, the decision matrix to evaluate routing algorithms, an MCDM approach to weight the criteria, and an MCDM approach to ranking routing algorithms. Figure 1.5 provides an overview of the research approach.

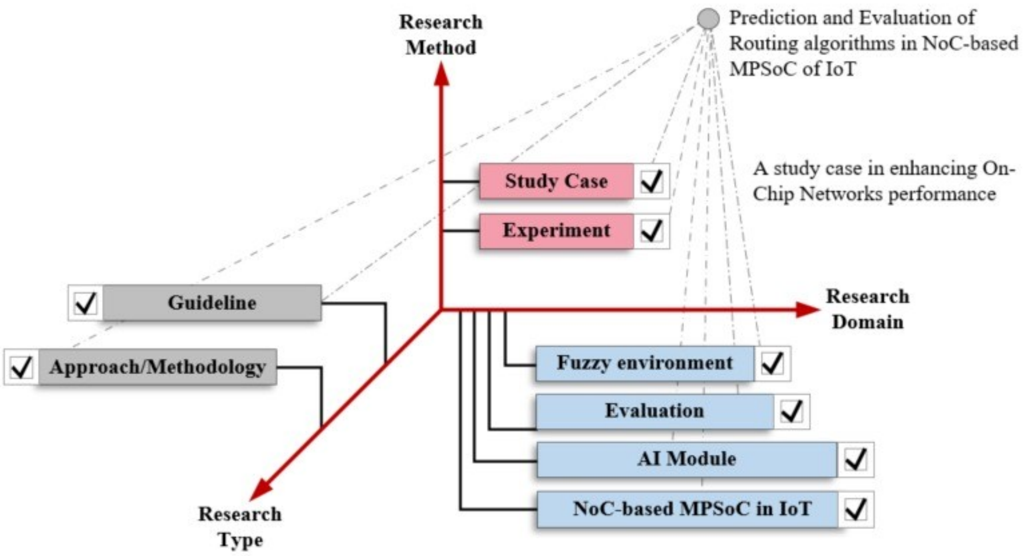

Figure 1.5 : Research Scope

In Figure 1.6, the cross-disciplinary approach integrates principles from computer science, fuzzy environment, and network theory to evaluate various routing algorithms for NoC-based MPSoCs rigorously. The study identifies the most efficient and inefficient routing protocols by systematically analyzing each algorithm's performance under different conditions. The focus is on time consumption and latency metrics, aiming to optimize data transfer speeds and minimize delays. This comprehensive evaluation helps develop more robust, high-performance NoC systems crucial for advanced multiprocessor architectures.

1.8 Significance of the Study and Research Contribution

1.8.1 The Theoretical Importance of the Study

This study will contribute by adopting a systematic literature review approach to provide an overview of the existing information and evidence regarding our mission and assessment and comparison approach and highlight trends for research work on this topic. This study will also contribute to filling the research gap in this field. The proposed classification of the relevant literature in this study could also bring many benefits. Additionally, it will identify potential research directions in this area, reveal research gaps, and map the literature on automated methods for evaluating routing algorithms in all its fields. In addition, this study will provide a guide to the most important criteria to be adopted to assess routing algorithms. Finally, the study presents the most important methods used recently in the field of decision-making. On the other hand, the theoretical significance of AI resides in the latter's potential to improve the precision, efficiency, and efficacy of prediction in complex systems. This method can aid academics and designers in gaining fresh understanding, seeing developing patterns, making better judgments, and building intelligent models. On the other hand, the theoretical significance of combining fuzzy sets with MCDM techniques resides in their capacity to deal with uncertainty and vagueness in decision-making situations. The fuzzy set theory provides a mathematical structure that enables decision-makers to show and manage ambiguous and vague information by allocating membership degrees to the different components of a set. Using fuzzy set theory with FWZIC and FDOSM techniques enables the interpretation of ambiguity and vagueness in the assessment of alternatives against various criteria and converting the opinion matrix to a fuzzy opinion matrix, while the concept of zero-inconsistency helps to ensure that the weights assigned to the various criteria.

1.8.2 The Practical Significance of the Study

Applying a decision matrix to assess routing algorithms is practical and important for judgment in NoC-based MPSoC. A decision matrix is a structure that enables decision-makers to systematically assess and distinguish between various alternatives according to various criteria. When employing the optimal routing algorithm in the context of a NoC-based MPSoC platform, the designers can gain the following practical significance:

1) Reduced Latency and Improved Throughput: Advanced routing algorithms can optimize the data paths and minimize the distance between communication endpoints, leading to reduced latency and improved throughput. This is especially critical in MPSoCs, where multiple processing elements need to communicate frequently, and any reduction in communication delays can enhance overall system performance.

2) Lower Power Consumption: Efficient routing algorithms can significantly impact power consumption by reducing unnecessary data movement and avoiding congested routes, leading to energy-efficient MPSoCs.

3) Enhanced Scalability: As MPSoCs grow in size and complexity, scalability becomes a major concern. Advanced routing algorithms ensure that as the number of processing elements increases, the communication infrastructure remains efficient and capable of handling the growing demands. This enables the creation of larger and more powerful MPSoCs without compromising performance.

4) Fault Tolerance and Reliability: NoCs are vulnerable to various faults, such as link failures or router malfunctions. Robust routing algorithms can adapt to these faults by finding alternative routes and maintaining communication even in the presence of failures. This fault tolerance enhances the reliability of the MPSoC system as a whole.

5) Quality of Service Support (QoS): Different applications in an MPSoC may have diverse requirements in terms of communication bandwidth, latency, and reliability. Advanced routing algorithms can support QoS by efficiently allocating network resources to meet the specific needs of different applications. This ensures that critical tasks receive the required resources and meet their performance targets.

6) The success of an ANN relies heavily on the hyperparameters that were chosen for it, so the last practical importance is to determine the hyperparameter of ANN easily and accurately by using GCAOA, which leads to a very accurate prediction process in order to support the designer to solve their problems.

7) Finally, the ZCR-FWZIC & ZCR-FDOSM-BM technique offers experts a more accurate and trustworthy method to improve decision-making. It works well in cases when there are many criteria being used, which may be difficult for more traditional models to manage decision-making. Expert judgments allow ZCR-FWZIC & ZCR-FDOSM-BM to capture a larger variety of information than mathematical models alone. Furthermore, the ZCR-FWZIC &ZCR-FDOSM-BM approach can improve efficiency in decision-making by decreasing the amount of time spent on the process and unnatural comparison.

1.9 Structure of Thesis

This research is composed of six chapters. These chapters are briefly reviewed as follows:

Chapter 1: Introduction: This chapter introduces the research background problem statement in addition to illustrating the research questions, objectives, and connectivity among research objectives, research questions, specific problems, and general problems. Moreover, this chapter presents the research scoop, the contribution to the body of knowledge, and the significance of the study.

Chapter 2: Literature Review: the analysis of a systematic review of the routing algorithms and MCDM methods and AI is present in this chapter. In addition, it will examine, analyze, and criticize the literature work and end with the open issues of evaluating the routing algorithms, ANN, and FWZIC & FDOSM.

Chapter 3: Research Methodology: describe the research methodology in detail, which consists of 4 main phases, namely, the investigation phase, the proposed routing algorithms evaluation criteria, the development phase that contains the development FDOSM & FWZIC, and the integration of the GCAOA with ANN, and evaluation and comparison study phase. Through the phases, this chapter will show precisely how the seven research objectives will be achieved.

Chapter 4: Results of Machine Learning: This chapter presents the results and discusses the benchmarking methodology for routing algorithms that were carried out. The chapter demonstrates how the results of the proposed methodology resolve the difficulties mentioned in the problem statement. In addition, the results of the proposed GCAOA-ANN are presented. Also, this chapter provides the results of the validation progression.

Chapter 5: Results of MCDM methods: This chapter presents the results and discusses the third phase in our methodology for routing algorithms. In addition, this chapter explains the results of ZCR-FWZIC and ZCR-FDOSM-BM. Also, this chapter presents the results of the validation process.

Chapter 6: Conclusion and Future Work: This chapter provides the study's conclusion and is followed by the highlights, the summary of research contributions, the limitations, and a discussion of future work. Figure 1.6 demonstrates the structure of the study.

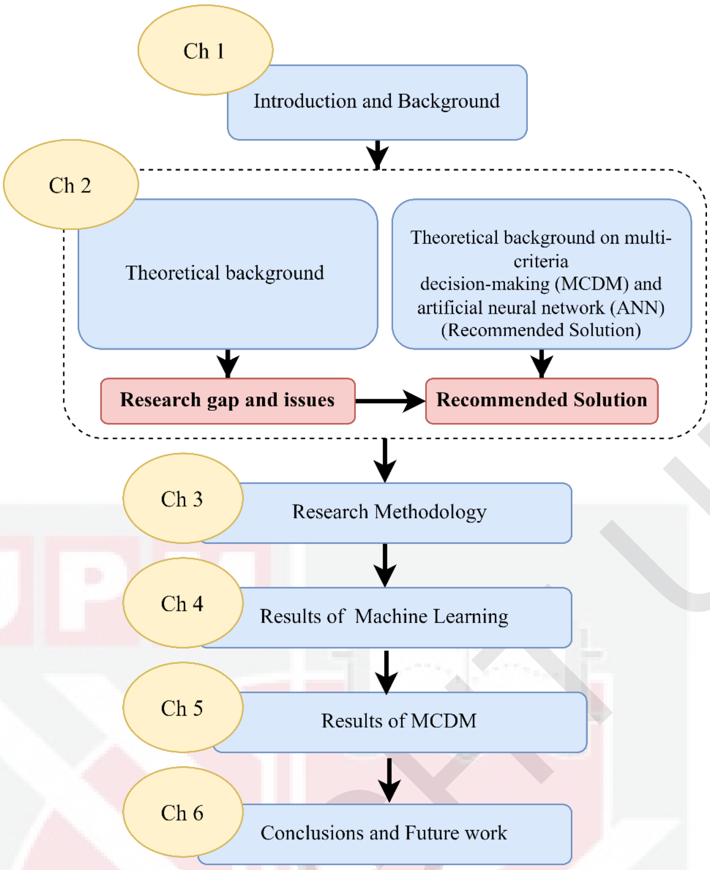

Figure 1.6 : Structure of the Thesis

1.10 Chapter Summary

This chapter presents the background of the study. Specifically, it describes the stages of development of NoC-based MPSoC over the past decades and how to manage the growing demand for high performance. Also, it represents the concept of routing algorithms and the criteria used in the evaluation process. The most vital point of this study's background is the importance of the routing algorithm in the NoC-based MPSoC sector. As such, different criteria might measure the same routing algorithm and show comparison results differently. This chapter also shows the need to predict and evaluate routing algorithms to avoid time consumption. Finally, the detailed explanations of the problem statement, the research objectives, the scope, and the study's significance.

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