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MULTI-CRITERIA ACCESS SELECTION MECHANISM BASED ON USER PREFERENCES IN HETEROGENEOUS WIRELESS NETWORKS

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Universiti Utara Malaysia

DOCTOR OF PHILOSOPHY

UNIVERSITI UTARA MALAYSIA

2023

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Abstrak

Pemilihan akses adalah salah satu teknologi kunci dalam rangkaian tanpa wayar heterogen. Pada masa ini, teknologi pemilihan akses kebanyakannya menggunakan parameter prestasi rangkaian tunggal dan umum sebagai kriteria pemilihan akses, mengabaikan keutamaan pengguna. Ia dengan mudah membawa kepada mengakses skim pemilihan yang tidak selaras dengan keperluan pengguna sebenar, dan ia tidak menambah baik pengalaman pengguna. Dalam tesis ini, mekanisma pemilihan capaian pelbagai kriteria yang menyokong ciri perkhidmatan dan pilihan pengguna telah direka bentuk. Mekanisme ini menggunakan fungsi utiliti, kaedah entropi, FAHP, dan teori logik kabur untuk mengira nilai utiliti, berat objektif, berat subjektif, dan skor atribut rangkaian, berdasarkan. FAHP dilaksanakan untuk menentukan nilai keutamaan pengguna, dan kaedah MADM digunakan untuk menetapkan skor rangkaian tersedia yang komprehensif. Eksperimen simulasi menunjukkan bahawa mekanisma yang dicadangkan membolehkan pengguna memilih rangkaian yang paling sesuai, mencapai laba yang lebih tinggi, dan mengurangkan penyerahan antara rangkaian yang berbeza berbanding dengan algoritma pemilihan akses lain. Mekanisma yang dicadangkan boleh menyokong pelbagai ciri-ciri perkhidmatan dan keutamaan pengguna pada masa yang sama,, dan sesuai untuk senario aplikasi Internet mudah alih generasi akan datang yang mengutamakan pengguna.

Kata Kunci: Proses hierarki analitik kabur, Logik kabur, Fungsi utiliti, Penyerahan tanpa wayar, Generasi mudah alih seterusnya.

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Abstract

Access selection is one of the key technologies in heterogeneous wireless network. At present, the access selection technology mainly adopts single and common network performance parameter as access selection criteria, ignoring the user preferences. It easily leads to access selection schemes that are out of line with the actual user requirements, and it does not improve user experience. In this thesis, a multi-criteria access selection mechanism supporting service characteristics and user preferences is designed. This mechanism uses utility function, entropy method, FAHP, and fuzzy logic theory to calculate the utility value, objective weight, subjective weight, and score of network attributes, respectively. FAHP is implemented to determine user preference values, and MADM method is used to establish the comprehensive candidate networks scores. The simulation experiments show that the proposed mechanism enables users to choose the most suitable network, achieve higher gain and reduce handover between different networks compared to other access selection algorithms. The proposed mechanism can support the diversity of service characteristics and user preferences at the same time, and is suitable for user centric next-generation mobile Internet application scenarios.

Keywords: Fuzzy analytic hierarchy process, Fuzzy logic, Utility function, Wireless handover, Next-Generation mobile.

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Declaration Associated with This Thesis

Some of the works presented in this thesis have been published or submitted as listed below.

[1] **Xiaoxue Guo**, Mohd. Hasbullah Omar and Khuzairi Mohd Zaini, "Multiattribute Access Selection Algorithm Supporting Service Characteristics and User Preferences in Heterogeneous Wireless Networks," Wireless Communications and Mobile Computing, vol. 2020, pp. 8887324, 2020, doi: 10.1155/2020/8887324. [Indexed by SCOPUS]

[2] **Xiaoxue Guo**, Mohd. Hasbullah Omar, Khuzairi Mohd Zaini, Gen Liang, Maoyuan Lin and Zirun Gan, "Multiattribute Access Selection Algorithm for Heterogeneous Wireless Networks Based on Fuzzy Network Attribute Values," IEEE Access, vol. 10, pp. 74071-74081, 2022, doi: 10.1109/ACCESS.2022.3186149. [Indexed by SCOPUS]

[3] **Xiaoxue Guo**, Mohd. Hasbullah Omar, Khuzairi Mohd Zaini, Jianfeng Gong, Jingcheng Fang and Gen Liang, "Access-Selection Algorithm for Heterogeneous Wireless Networks Based on Uncertain Network Attribute Values," Computational Intelligence and Neuroscience, vol. 2022, pp. 4646889, 2022, doi: 10.1155/2022/4646889. [Indexed by SCOPUS]

Acknowledgement

More efforts and sacrifices have been made to complete the research of this thesis than I expected. This research would not have been completed without the contributions of many people.

I am very grateful to my supervisors: Professor Mohd. Hasbullah Omar and Dr. Khuzairi Mohd Zaini gave me a lot of encouragement and advice during my research. In the whole process of completing this thesis, they have always provided me with continuous, constructive and valuable guidance, opinions and suggestions.

I would like to thank and appreciate all the staff of Universiti Utara Malaysia, especially the staff of the School of Computing, for their support to me. In addition, I would like to thank InterNetWorks Research Laboratory for its advice and help during my research.

Thanks to my most beloved parents, you gave me life, all my achievements today are inseparable from your dedication. Thank you to my husband and two lovely sons for making my life colorful and for the great support you have given me so that I can achieve my dreams.

Finally, I would like to thank all the other friends who contributed to this research, who shared their efforts, time and ideas for this research. Thank you all. May Allah bless all of you.

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List of Abbreviations

1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	The 3rd Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
AHP	Analytic Hierarchy Process
AP	Access Points
BER	Bit Error Ratio
CDMA	Code Division Multiple Access
CI	Consistency Index
CR	Consistency Ratio
DRM	Design Research Methodology
DS-I	Descriptive Study-I
DS-II	Descriptive Study-II
FAHP	Fuzzy Analytic Hierarchy Process
FDMA	Frequency Division Multiple Access
GRA	Gray Relation Analysis
GSM	Global System for Mobile Communication
HHO	Horizontal Handoff
HWN	Heterogeneous Wireless Network

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IEEE	Institute of Electrical and Electronics Engineers
LTE	Long Term Evolution
MADM	Multiple Attribute Decision Making
MCASM	Multi-Criteria Access Selection Mechanism
MDP	Markov Decision Process
MEW	Multiplicative Exponent Weighting
MIMO	Multiple-Input Multiple Output
MMT	Multi-mode Mobile Terminal
OFDM	Orthogonal Frequency Division Multiplexing
PS-I	Prescriptive Study-I
QoE	Quality of Experience
QoS	Quality of Service
RAT	Radio Access Technology
RC	Research Clarification
RI	Random Index
RSS	Received Signal Strength
SAW	Simple Additive Weighting
SINR	Signal to Interference plus Noise Ratio
SNR	Signal to Noise Ratio
TDMA	Time Division Multiple Access
TFNs	Triangular fuzzy numbers
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution

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UMTS	Universal Mobile Telecommunications System
VHO	Vertical Handoff
WiFi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network

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CHAPTER ONE

INTRODUCTION

With the development of numerous wireless communication technologies in recent years, various wireless networks have emerged, such as Wireless Metropolitan Area Network (WMAN), cellular network, Wireless Local Area Network (WLAN). These wireless networks coexist and form a heterogeneous wireless network (HWN) [1, 2]. At the same time, mobile devices are also expanding their wireless access capabilities, which can support access to a variety of different wireless networks. In many research directions of HWN, access selection is one of their research hotspots [3, 4]. The main research content of this thesis is to design an access selection algorithm and test its performance in a HWN environment. This chapter introduces the research background of the thesis and the significance of conducting the research. This chapter first outlines the development of wireless communication networks, and then briefly describes the HWN architecture. Section 1.2 points out the research motivation of this article and summarizes the necessity of researching and designing access selection algorithms. In Section 1.3, we describe the problem statement and introduced the current issues and challenges of access selection. In Section 1.4, we discussed research questions. Subsequently, the research objectives, scope, and steps were briefly described in sections 1.5, 1.6, and 1.7, respectively. Section 1.8 emphasizes the main significance of this research. Finally, Section 1.9 provides an overview of the organizational structure of the thesis.

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1.1 Overview of Wireless Network Technology

1.1.1 Various wireless communication networks

To enable seamless information exchange anytime and anywhere, wireless communication has been widely concerned and developed rapidly. In recent years, the trend of wireless network technology diversification has become increasingly obvious, forming a multi-network system including cellular network, WLAN and WMAN.

i. Cellular Network

The first-generation mobile system (1G) used analog frequency modulation and Frequency Division Multiple Access (FDMA) to provide voice transmission services. The second-generation mobile system (2G) adopts Code Division Multiple Access (CDMA) and Time Division Multiple Access (TDMA) technologies to upgrade from 1G analog communication technology to 2G digital communication technology. The third-generation mobile system (3G) has the ability to support multimedia services, can support the transmission of voice and data information (such as email, instant messaging), and can provide data service transmission services up to several hundred kbps or higher.

It's worth noting that the 3rd Generation Partnership Project (3GPP) established the Long-Term Evolution (LTE) standard, which uses technologies like Multi-input Multi-output (MIMO), Orthogonal Frequency Division Multiplexing (OFDM), and others to further improve the data transmission rate and spectrum efficiency. LTE is a long-term evolution of the Universal Mobile Telecommunications System (UMTS) standard. Additionally, LTE-Advance also switches to the fourth generation of mobile communication technology while remaining compatible with LTE. The fourth-generation mobile communication system (4G) offers at least ten times the system capacity of 3G systems, supports broadband access for users in high-speed mobile situations, and enables users to seamlessly switch between systems based on their service requirements [5].

The International Telecommunication Union working group IMT-2020 promoted the fifth-generation mobile communication (5G) standard, and many communication companies are fully involved in the development of 5G international standards and technology development. In the era of continuous technological advancements, such as large-scale antennas and network coding, 5G systems have significantly outperformed 4G systems in all performance metrics [6, 7].

A comparison of key technologies for cellular network is demonstrated in Table 1.1.

Table 1.1

The Development of Mobile Communication Technology

Generation	Technical Standard Name	Proposed time	Data rate (peak)	Service type
1G	AMPS TACS	1980s	-	Voice
2G	GSM N-CDMA	1990s	-	Voice, SMS, Data
2.5G	GPRS		100kbps	
2.75G	EDGE		1Mbps	
3G	UMTS WCDMA TD-SCDMA CDMA2000	1999	300Kbps-2Mbps	Audio, Video, Data
3.5G	HSPA	2000(HSDPA, R5) 2001(HSUPA, R6)	14.4Mbps (DL) 5.4Mbps (UL)	
3.75G	HSPA+	2002(R7)	168Mbps (DL) 22Mbps (UL)	
4G	LTE	2007(R8)	300Mbps (DL) 75Mbps (UL)	High quality audio and video, Data, wearable equipment
	TTE-A	2010(R10)	3Gbps (DL) 1.5Gbps (UL)	
4.5G	LTE-A Pro	2015(R13)	10Gbps (DL)	
5G	-	-(R15)	Dozens of Gbps	Large traffic data, wearable devices, Internet of Things

ii. Wireless Local Area Networks

While mobile cellular networks continue to evolve, wireless local area networks have also achieved high-speed development due to their better flexibility than traditional wired LANs [8, 9]. WLANs are most typically represented on the basis of the IEEE802.11 series of standards and use the 2.4GHz or 5GHz frequency band for communication. A widely used standard is 802.11b, which has a carrier frequency is 2.4GHz and transmission speed is 11Mbps; 802.11e adds a Quality of Service (QoS) guarantee function in the MAC layer; 802.11n increases transmission rate to more than 300Mbps by combining MIMO and OFDM technology; 802.11ac employs additional MIMO streams and improved modulation to achieve a theoretical single-channel rate of 500Mbps [10].

iii. Wireless Metropolitan Area Network

A wireless network with scattered nodes that covers cities and their suburbs is referred to as a WMAN. World Interoperability for Microwave Access (WiMAX) technologies belong to the category of WMAN [11]. WiMAX has fast data transmission speed and wide coverage, but it is limited by its voice support ability and mobility. WiMAX focuses on the "last mile" broadband wireless access, which can provide wireless technology covering tens of kilometers without access through DSL or cable infrastructure. The IEEE 802.16 working group released WiMAX series standards such as 802.16, 802.16a, 802.16d, 802.16e and 802.16m, among which 802.16m standard can support wireless transmission rate over 1Gbps [12].

Although cellular mobile communication technology and broadband wireless access technology evolve in different directions, providing personalization and diversified services for users in different scenarios, their ultimate evolution direction tends to be consistent. Mobile, broadband and unified all-network are the main characteristics of future mobile communication technology [13-15].

In summary, different networks have their own characteristics in performance, coverage, data rate and mobility support, and their application occasions also have their own emphasis. It is difficult to replace each other and cannot meet the requirements of personalization and diversified services in future mobile communications only by a single network. Therefore, the development goal of the next generation mobile communication technology is not to build a new, unified and powerful network with perfect functions, but to integrate existing HWN, complement each other, work together, and ultimately achieve the objective of any kind of data exchange with anybody anytime and anywhere [16, 17].

1.1.2 Heterogeneous Wireless Network

The next generation wireless networks will be HWN coexisting with public mobile communication networks (such as 2G, 3G, 4G, 5G), WLAN (such as Wi-Fi), WPAN (such as Bluetooth), WMAN (such as WiMAX) and Ad Hoc networks. The important reason why the next generation wireless network becomes the convergence of HWN is that: based on heterogeneous network convergence, users can choose appropriate networks and provide better QoS according to user characteristics (e.g., on-board users), service characteristics (e.g., high real-time demand) and network characteristics.

At present, there are many kinds of access networks in mobile communication system, each of which has unique qualities and potential uses. However, no single mobile communication access network can provide users with comprehensive services of high bandwidth, wide coverage, high transmission quality and multi-type services at the same time. Therefore, the future mobile communication network must be a heterogeneous architecture, as can be seen in Figure 1.1. Various mobile communication networks adopt corresponding technologies to connect with the public core network as access network [18, 19].

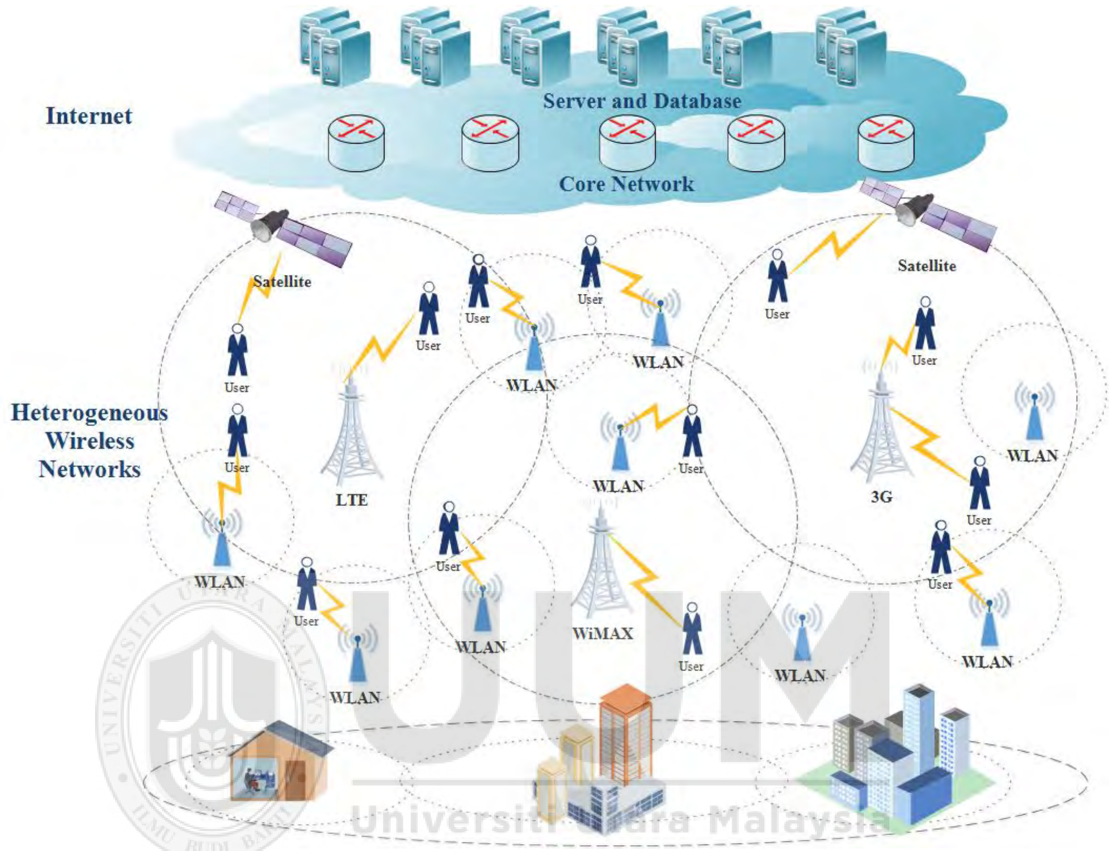

Figure 1.1. Architecture of Heterogeneous Wireless Network

1.2 Research Motivation

Due to the heterogeneous cascading of wireless access signal ranges, an important issue is how to effectively manage users in HWN, thereby improving network service efficiency and guaranteeing QoS. With the development of the mobile Internet, users are more concerned about the service itself and its own experience, rather than a single, common network performance indicator. User evaluation for QoS depends not only on the efficiency of service acquisition, but also on whether the results are closely related to user requirements. That is, users are more inclined to accurately match their own requirements through the reasonable adaptation of network and service performance, so as to obtain the ultimate user experience [20].

Since 2012, the EU has started projects such as METIS and 5G-AURA, focusing on user-centered communication theory and corresponding technical systems. The METIS project aims to improve the user experience by studying key technologies such as multi-node and multi-antenna transmission, multiple access and multi-layer networks. The 5G-AURA project pays more attention to the research of programmable network architecture, and realizes application awareness and user experience through cloud computing, software-defined network, and network virtualization. In the international academic community, IEEE Communications Magazine launched a special issue on "Human-Driven Edge Computing and Communications" in February 2018. IEEE Journal on Selected Areas in Communications also launched a special issue on "Human in the Loop Mobile Networks" in April 2017. In addition, IEEE Globecom, IEEE ICC, and other communications association flagship conferences have set up a topic on quality of experience (QoE), attracting the participation of many scholars. Huawei not only plays a leading role in the research projects of METIS, but also cooperates with Telefonica to conduct research on 5G User Centric and No cell.

In an environment of increasingly fierce commercial competition between network operators and service providers in the communications industry, in order to better attract and retain more users, satisfying user personalization service requirements and enhancing user experience have become the focus of competition and development in the industry [21]. The IMT-2020 promotion group pointed out: "5G will penetrate into all areas of the future society and build a comprehensive information ecosystem with users as the center." The TeleManagement Forum is the world's leading telecommunications industry organization. The organization is also evolving QoS management into user experience management and establishing user-centric satisfaction management metrics.

This research focuses on the users served by the communication system in HWN. The core research direction of this research is to establish user-centered access selection scheme based on service characteristics and user preferences, which is consistent with the long-term development trend of communication industry. It has important theoretical significance and application value. In this research, aiming at solving the key problems of poor user experience, unreliable quality of service and low resource utilization efficiency in HWN, a new access selection mechanism based on user preference is obtained, which becomes the motivation of this research.

1.3 Problem Statement

In the scenario of HWN, mobile terminals with multi-mode interfaces can access different networks for data transmission [22]. Therefore, how to make mobile terminals in HWN access the most suitable network is a key problem, as shown in Figure 1.2. To choose the most suitable network, we should take into account the following three aspects: service characteristics, network attributes and different user preferences.

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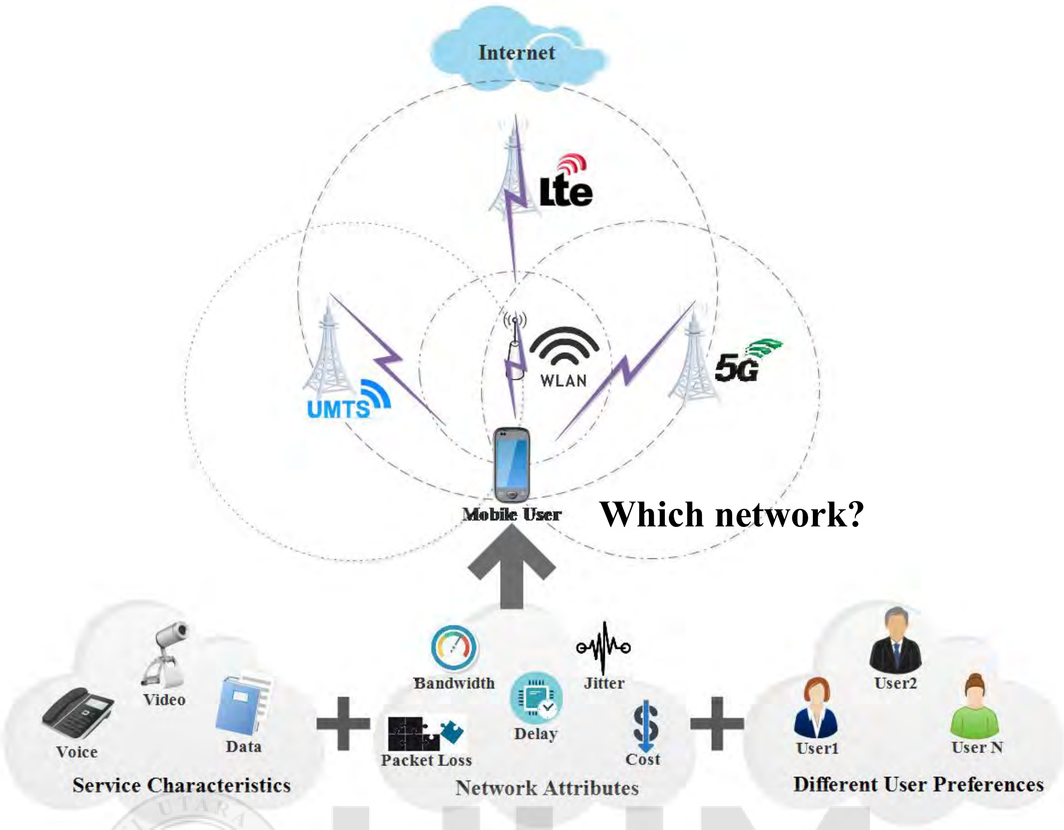

Figure 1.2. Network Selection Problem in HWN

Most existing access selection mechanisms either consider only single criterion, or did not take into account services characteristics, or did not take into account the user preferences. Further, the specific problem statement is listed as follows:

Firstly, some algorithms use a single criterion for access selection. For example, Roy et al. [23] connect users to the highest RSS network. Gerasimenko et al. [24] connect users to the lowest load network. Although these access selection algorithms based on a single criterion have lower computational complexity, they only take into account one aspect of the network's performance and do not adequately consider the comprehensive performance of the network. Future HWN will contain more and more networks with different architectures, and each network has its own advantages in different performance aspects, and the access selection algorithms based on a single criterion cannot fully evaluate the comprehensive performance of the network.

Therefore, we need a multi-criteria access selection mechanism.

Secondly, although some algorithms use multiple network attributes for access selection, for example, Senouci et al. [25] consider multiple network attribute criteria, hoping that users can connect to the network with the highest comprehensive performance. However, with the continuous development of network applications, there will be more and more different services, and different services have different network performance requirements, such as real-time guarantees for some user services, high bandwidth guarantees for some user services, and lower service prices guarantees for others [26]. At present, some access selection algorithms [27, 28] only assume that the user service is a single type of service, without fully considering the diversity of user services, failing to access the most suitable network for the service, resulting in failure to guarantee the QoS. Therefore, when designing access selection algorithms, we need to consider the diversity of service characteristics.

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Finally, some literature considers different services when designing access selection algorithms. For example, Lahby et al. [29-31] consider the three services of voice, video and best effort, and are able to access the most suitable network for the service characteristics. However, different users tend to have different preferences for network attributes and networks [32]. For example, for the same video service, some users have higher requirements for video clarity, while others have higher requirements for smoothness. When the network performance is certain, accessing the same network for two kinds of users may result in poor user experience and loss of users. In addition, users have different experiences and habits in using different networks [33-35]. At present, access selection algorithms often do not take into account the differences of user preferences and fail to improve the user experience. Therefore, when designing access selection algorithms, we also need to consider the differences of user preferences [36].

In summary, the main problem in access selection is the need for an effective multi-criteria access selection mechanism in HWN that considers the diversity of service characteristics and the differences of user preferences at the same time.

1.4 Research Questions

The major research question is how to design a multi-criteria access selection mechanism in HWN based on service characteristics and user preferences? Furthermore, the specific research questions are as follows:

i. What are the important attributes of user service characteristics?

ii. How to reflect the differences of user preferences for network attributes and candidate networks?

iii. How to evaluate the performance of proposed mechanism?

1.5 Research Objectives

The overall objective of this research is to design a new multi-criteria access selection mechanism in HWN based on service characteristics and user preferences. By connecting mobile users to the most suitable network to meet the requirements of different services and improve the quality of user experience, so as to provide the theoretical guidance of access selection mechanism in HWN. Further, the specific objectives are as follows:

i. To design an access selection scheme to support the diversity of service characteristics.

ii. To design an access selection scheme to support the differences of user preferences.

iii. To evaluate the performance of proposed multi-criteria access selection mechanism and compare comprehensively with some of the existing strategies in the simulation network environment.

1.6 Research Scope

The main objective of this research is to design a new multi-criteria access selection mechanism in HWN that supports different service characteristics and user preferences. In HWN, access typically involves three stages: network discovery, access decision, and execution. This research concentrates on access decision stage.

The access decision stage is where the best network is chosen after executing an access selection mechanism based on the data gathered, including network quality, terminal state, service type, and user preference. The quality of the network selection mechanism in the access decision directly affects whether the user can access the most suitable network, and also affects the effective use of the entire network resources. Therefore, the access selection mechanism in HWN is one of the essential technologies related to the user experience, which is also the main focus of this research.

In addition, for user service types, this research is based on the classification criteria of mobile services of 3GPP. The research scope mainly focuses on background traffic service, conversational traffic service, streaming traffic service and interactive traffic service, and analyzes the characteristics and differences of these four types of services.

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The research scope for candidate networks includes UMTS, LTE, WiMAX, and WLAN. UMTS and LTE are both based on 3GPP standard. UMTS is the typical representative of 3G, and LTE is the typical representative of 4G. WiMAX is a typical representative of WMAN. WLAN is the most widely used LAN at present. So, these four networks are typical representatives of cellular network, WMAN and WLAN. In real application scenarios, these four network signals coexist in the same area.

For the decision parameters, bandwidth, packet loss ratio, delay, jitter and price are taken as the decision parameters of access selection in this research, because these five judgment parameters are closely related to user services and are adopted by most relevant literature.

Finally, this research uses MATLAB as simulation platform to evaluate the performance of the algorithm.

1.7 Research Steps

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In order to achieve the research objectives mentioned above, in this article, we plan to take the following detailed research steps:

i. Classify and analyze in detail the references of access selection in HWN;

ii. Study in depth the advantages and disadvantages of utility theory, multi-attribute decision making, fuzzy logic and other theories in the design of access selection algorithm.

iii. Study the characteristics of different user services, and the utility values of each network attribute under different user services

iv. Study the calculation method of subjective weight and objective weight of network attributes in the design of access selection algorithm.

v. Study the calculation method of different users' preference values for network attributes and candidate networks in access selection.

vi. Comprehensively study the multi-attribute decision making method and give a ranking method of candidate networks.

vii. Build the simulation environment based on MATLAB and evaluate the performance of proposed mechanism.

1.8 Research Significance

According to the Wireless World Research Forum (WWRF), the next-generation mobile communication is being developed with the goal of smoothly integrating new and existing wireless access networks, making use of the respective advantages of different networks to provide users with high-quality and diversified service requirements. At the same time, future services will not only be a single type of services, but also contain a variety of services. Therefore, how to ensure the effective transmission of multiple services in HWN will become a hub for future research, and the first step of transmission is how to design an effective access selection.

If the access selection mechanism does not consider the three aspects of network, service and user at the same time. For the wireless network, it will reduce the utilization ratio of network resources; for the service, it will fail to guarantee the QoS; for the user, it will affect the user experience. Access selection will be one of the most important fundamental concerns in the creation of the next-generation network, whether viewed from the perspective of users or operators.

At present, the traditional access selection mechanism cannot meet the requirements of more and more service types. At the same time, with the development of wireless communication technology and the emerging new services, there is an urgent need to provide a new access selection mechanism. This research designs a new access selection mechanism to support service characteristics and design a calculation scheme for user preferences, which enable multi-mode terminals to access the most suitable wireless network in HWN according to the current network performance, service characteristics, and user preferences [37]. Therefore, the proposed access selection mechanism can improve the QoS and the QoE [38, 39]. This underscores the significance of the research.

1.9 Organization of the Thesis

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The six chapters that make up this thesis are broken down into the following basic sections:

Chapter One provides a summary of the thesis. It specifically introduces the concept of HWN and the advancement of wireless network technology. In addition, the motivation for the research, problem statement, research question and objectives, and the significance of the research are all covered in this chapter.

Chapter Two offers a comprehensive overview of access selection in the HWN environment. Firstly, the related concepts of access selection are introduced. Secondly, the basic principles of access selection algorithms under various models are described in detail, and the references of various algorithms are analyzed and compared. Finally, the issues with the network selection algorithm's design are summarized, and further research directions are proposed.

Chapter Three provides a detailed introduction to the research methodology used to achieve the predetermined objectives of this thesis, and proposes a method for designing access selection algorithms based on descriptive study and prescriptive study.

Chapter Four designs a multi-criteria access selection mechanism that supports user preferences and service characteristics in HWN, and introduces the network attribute utility value, network attribute weight, network attribute score, user preference value, and candidate network comprehensive score calculations of the algorithm.

Chapter Five introduces the simulation experimental environment and detailed parameter settings, and compares to other mechanisms and measures the performance of the proposed mechanism.

Chapter Six Summarizes this thesis, emphasizing the contributions and limitations related to this research, as well as the work that needs to be further improved in this research direction.

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CHAPTER TWO

LITERATURE REVIEW

The first chapter introduces the overall research plan of this thesis. This chapter will analyze the access selection in HWN, which will help to determine the overall framework of this thesis. In this chapter, Section 2.1 briefly introduces the access selection technology of HWN. Section 2.2 describes the principle, process and judgment parameters of access selection. In Section 2.3, the access selection algorithms are thoroughly analyzed and contrasted. Section 2.4 summarizes the current issues and future research trends. Section 2.5 compares the relevant research work. Finally, Section 2.6 provides a summary of the total literature evaluation in this chapter.

2.1 Background

Because various wireless networks have varying signal coverage, transmission rate, mobility support, price and other aspects, and their main applications are also different, any single network cannot simultaneously accommodate all users' varied business demands. Additionally, the development goal of wireless communication technology in the future is not to re-establish a network with strong performance, complete functions and suitable for any user business type, but to connect various existing wireless network systems, effectively integrate the resources of various network systems, so that they can not only give full play to the respective advantages of a single network, but also work together with other networks to complement each other, finally, it can provide users with diversified and high-quality communication services in various application scenarios.

Heterogeneous wireless network refers to a wireless communication system with overlapping signal range coverage comprised of wireless networks with various protocols and architectures, such as WLAN, mobile cellular networks, WMAN and satellite communication networks.

2.2 Principle of Network Access Selection

2.2.1 Overview of Access Selection

In a HWN environment, multiple wireless networks' signals can be simultaneously received by mobile user terminals. However, since the good or poor transmission quality of wireless channels, variations in wireless networks' processing capabilities, and divergent service demands of users, users must select the best network from a variety of candidate networks, i.e., the access selection, as shown in Figure 2.1. Hence, one of the core technologies of HWN is access selection [3].

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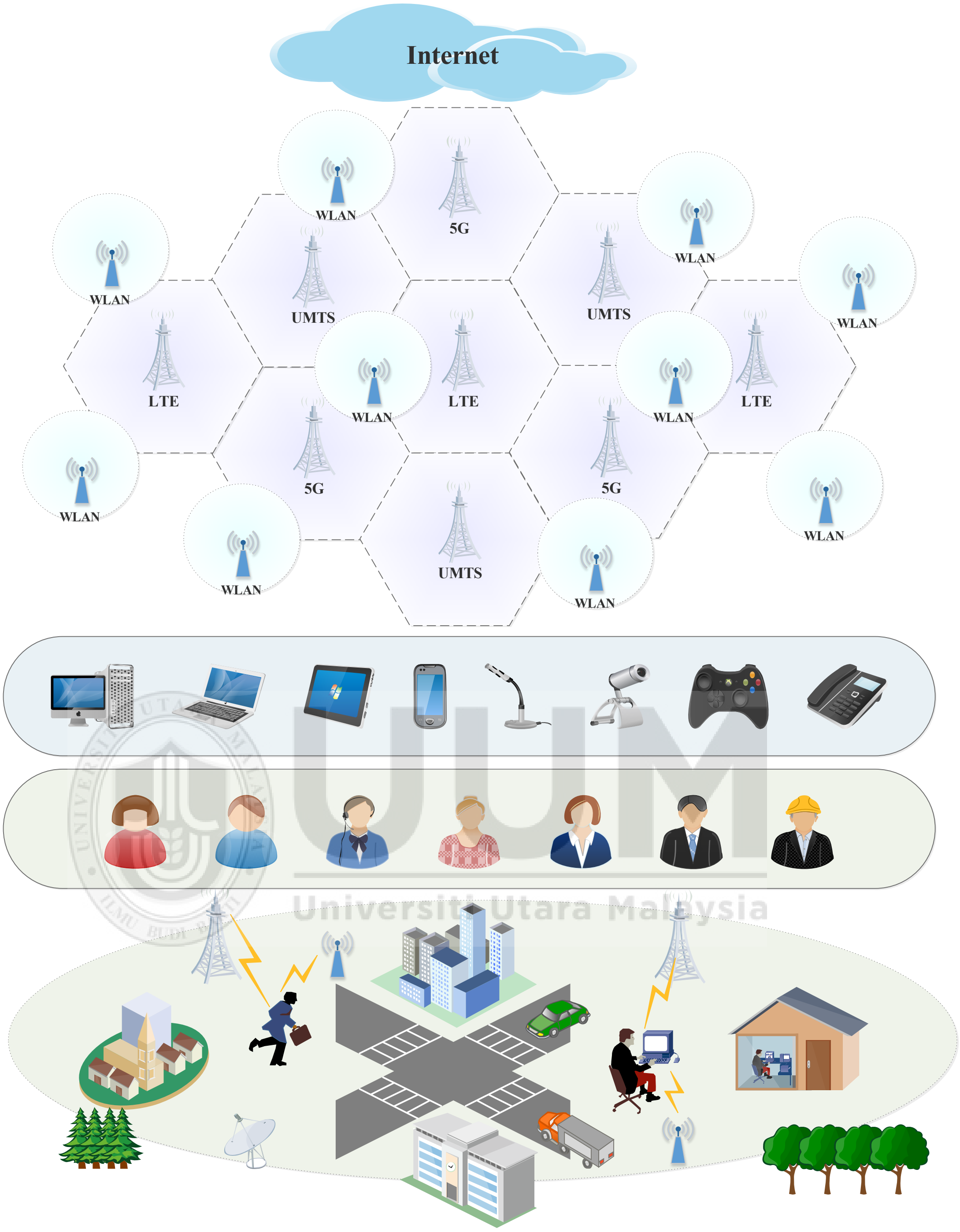

Figure 2.1. HWN Access Selection Scenario

For the purpose of a mobile user terminal to support network selection, the user terminal device must have multiple interfaces that support different standard networks, therefore, such user terminals are called multimode terminals [40]. The process of selecting a multimode terminal to access different networks involves horizontal handoff (HHO) between homogeneous wireless networks and vertical handoff (VHO) between heterogeneous wireless networks [41, 42].

2.2.2 Access Selection Process

Access selection can be divided into two categories: access selection for mobile terminal initiating initial connection and access re-selection for mobile terminal switching to another network. Three stages can be identified in the access selection process: decision information collecting, decision making, and decision execution [43, 44], as shown in Figure 2.2.

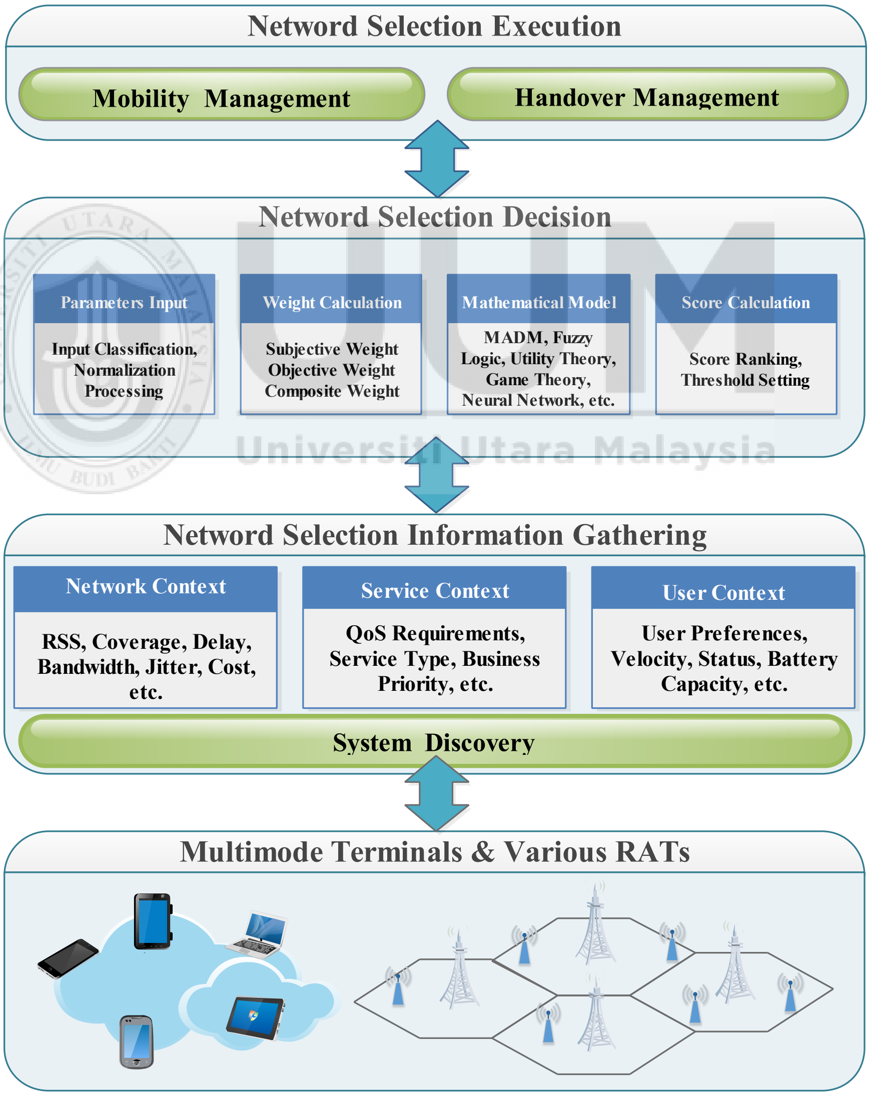

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Figure 2.2. Stages of Access Selection

In the initial phase, the information collection module is responsible for collecting, managing, and analyzing the gathered data. During this phase, network information (e.g., RSS, coverage, delay, bandwidth, jitter, price), service information (e.g., service type and QoS guarantees), user terminal device information (e.g., remaining battery capacity and mobile speed), and user context information (e.g., user preferences and user location) are stored and managed before being transmitted to the network selection decision unit.

The second phase is the core of the network selection process, in which the access selection algorithm makes a network selection decision by combining various decision factors to determine whether the mobile user should transfer to a better network or stay connected to the current network [28], and sends the decision result to the execution unit.

In the third phase, the user is assisted in completing the network connection based on the decision made in the second step and in compliance with the applicable wireless network's communication protocol processes.

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Among the three phases, the network selection decision making phase is crucial, and the results of the second stage determine whether it can meet user needs and achieve the best network connection performance [45].

2.2.3 Decision Parameters for Access selection

In homogeneous wireless networks, the network access selection decision parameter is primarily related to the wireless link's quality, including the signal to noise ratio (SNR), received signal strength (RSS), and other factors. Its main purpose is to maintain the physical connection of the current wireless link. With the evolution of wireless networks, networks will progressively be accessible in the future, and there may be switching between different network management domains and technologies [46]. Therefore, the decision of access selection cannot be based on a single metric but instead requires considering multiple metrics for accessing the appropriate network. For the formulation of access selection decisions in HWN, the parameters that are usually considered include RSS, bandwidth, delay, jitter, network load, price, bit error ratio (BER).

In addition to those mentioned above, the decision parameters used by the access selection algorithm include energy consumption, user speed, security level, blocking rate [47]. Table 2.1 displays the decision parameters used in each reference.

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Table 2.1

Access Selection Decision Parameters

Ref	RSS	Bandwidth	Delay	Jitter	Loss	Error	Load	Energy	Price	Speed
[48]		●	●	●	●			●	●	
[49]	●						●	●	●	●
[27]		●						●	●	●
[50]		●						●		●
[51]		●	●	●	●			●	●	
[52]		●	●	●	●	●			●	
[53]	●	●	●					●	●	
[54]		●	●					●		
[36]		●	●	●	●				●	
[55]			●	●	●	●	●		●	
[56]	●	●	●	●	●		●		●	
[57]		●						●	●	
[58]			●		●			●	●	
[59]	●	●	●	●	●					●
[60]		●	●	●	●	●			●	
[60]			●					●	●	

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2.3 Survey of Access Selection Algorithms

Current research on access selection algorithms for HWN has been conducted by a large number of scholars, and these algorithms have been discussed in some published works.

For instance, Ahmed et al. [62] analyzed switching types, switching characteristics, and switching determination metrics for HWN, and analyzed and compared switching algorithms on the basis of RSS, QoS, decision functions, network intelligence, and context. Wang et al. [63] investigated various mathematical models used for network selection problems, compared access selection methods based on various mathematical models by designing a unified scenario and discussed access selection methods that combine multiple mathematical models together. Fernandes et al. [64] reviewed the mobility management-related technologies for HWN, proposed a heterogeneous interoperability architecture, and provided a comparative analysis of the latest protocols supporting advanced mobility management. Moreover, Ferrus et al. [65] commented on interoperability mechanisms to achieve seamless mobility in a HWN, and developed a framework that considers the interoperability of different standardization organizations, and proposed solutions for the convergence of WLAN, WiMAX, and 3GPP LTE. Kassar et al. [66] reviewed the concept of vertical handoff, handoff process, and handoff timing in HWN, and analyzed the theoretical model for vertical handoff decision. Additionally, Zekri et al. [67] analyzed the composition architecture, communication methods, and decision parameter classification of HWN, as well as studied the models based on utility function, multi-attribute decision, Markov Decision Process (MDP), fuzzy logic. The complexity, flexibility and reliability of various algorithms are analyzed and compared.

In this chapter, we categorize access selection algorithms according to Received Signal Strength, multi-attribute decision, utility theory, fuzzy logic, game theory, and neural network. The basic ideas of various access selection algorithms are described in detail, and the main references are analyzed in-depth, and ultimately, some problems and future research directions in access selection research of HWN are summarized.

2.3.1 RSS-based Access Selection Algorithm

The fundamental idea of the traditional RSS-based access selection algorithm is that the user terminal measures the RSS value of each candidate network and selects access to the network with the highest RSS. Furthermore, if the RSS of the candidate network is higher than the RSS of the currently connected network (i.e., $RSS_{new} > RSS_{old}$), then change networks to the one with the highest RSS. In the RSS-based access selection algorithm, the user detects that the RSS will continue to change, causing the user to frequently switch between networks, which can easily result in a severe ping-pong effect.

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Lee et al. [68] built on the traditional RSS-based access selection algorithm and proposed an adaptive lagging algorithm on the basis of the mobile correlation. This algorithm adds hysteresis timing H to the highest RSS algorithm, and users are connected to the new network only when $RSS_{new} > RSS_{old} + H$. The increase of lag time H in this algorithm can reduce the ping-pong effect, but it also increases the time delay, and the larger the H, the larger the time delay.

Roy et al. [23] proposed an access selection algorithm that incorporates hysteresis timing and is based on RSS and signal strength ratio, which has better performance than the fixed hysteresis timing-based algorithm in the network environment where

WLAN and 3G coexist, with different sampling intervals for RSS measurement by mobile terminals, and evaluates the calculation of hysteresis delay and limits the number of switching between different networks.

Ahuja et al. [69] proposed an access selection algorithm based on mobile user distance, average RSS, and outage probability, which consists of two phases, in the first phase, distance estimation is performed for the signal overlap region, and in the second phase, the preeminent network is selected based on the average RSS of the candidate networks.

Moreover, Hosny et al. [70] proposed two handover prediction schemes, the first of which depends on the signal quality between the user and nearby base stations, and the second of which is based on a multi-criteria prediction decision employing the station's bandwidth as well as the SNR. The scheme proposed in this literature employs two independent thresholds, the first of which is determined by the signal strength of the base station that is currently in use, while the second is determined by the user's measurement of the candidate base station's signal strength.

The RSS-based access selection algorithm has uncomplicated steps and low computational complexity, but it is easy to trigger the ping-pong effect, although some literature increases the switching threshold or hysteresis value in order to reduce the ping-pong effect, it also enlarges the switching delay. Moreover, such algorithms do not consider factors such as user preferences and service requirements, and the calculation results are more one-sided [71].

2.3.2 MADM-based Access Selection Algorithm

Since the decision making process for access selection involves a number of decision parameters, the access selection of HWN can be modeled as a multiple attribute decision making (MADM) problem. In designing the access selection algorithm using MADM, there are three main steps: in the first step, the decision parameter is normalized; in the second step, the weights of the decision parameter are calculated; and in the third step, the candidate networks are ranked [72, 73].

2.3.2.1 Normalization of Decision Parameter

MADM initially collects data of each decision parameter, and since the standard units of each decision parameter are divergent, we cannot calculate these decision parameters without deviation, so the first critical step of the MADM method is to standardize these parameters. Commonly used normalization methods include: max-min normalization, square root normalization and sum normalization, as indicated in Table 2.2.

Table 2.2
Decision Parameter Standardization Methods

Method	**Normalization Function**
Max-Min	$r_{ij} = (x_{ij} - \min x_{ij})/(\max x_{ij} - \min x_{ij})$ $r_{ij} = (\max x_{ij} - x_{ij})/(\max x_{ij} - \min x_{ij})$
Square root	$r_{ij} = x_{ij} \Big/ \sqrt{\sum_{i=1}^{N} x_{ij}^2}$
Sum	$r_{ij} = x_{ij} \Big/ \sum_{N}^{i=1} x_{ij}$

In the table, the x_{ij} represents the value of the jth parameter of the candidate network i, and r_{ij} represents the value of the parameter after the normalization process. After normalizing each decision parameter, a standardized Multiple Attribute Decision Making matrix can be formed. Suppose there are m candidate networks and n decision parameters, then the decision matrix of $R = (r_{ij})_{m \times n}$can be formed, as shown in the following equation.

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1j} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2j} & \cdots & r_{2n} \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ r_{i1} & r_{i2} & \cdots & r_{ij} & \cdots & r_{in} \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mj} & \cdots & r_{mn} \end{bmatrix} \quad (2.1)$$

2.3.2.2 Weight Calculation of Decision Parameter

In network access selection, the different decision parameters often have varying significance, therefore, the MADM method also determines the corresponding weight value of a decision parameter according to its importance to the user. There are two methods for determining weights: the subjective weighting method and the objective weighting method [74].

According to the decision maker's knowledge, experience, or preference in accordance with the level of relevance, the subjective weighting method compares, assigns, and calculates the weight of each decision parameter. Commonly used subjective weighting methods are the expert investigation method, the analytic hierarchy process (AHP), the preference ratio method, the decision alternative ratio evaluation system, the binomial coefficient method, the comparison matrix method, and the importance ranking method. The objective weighting method establishes weight based on the divergence of objective data of decision parameters. Commonly used objective weighting methods include principal element analysis, scatter degree method, entropy method, maximizing deviation method, and mean square deviation method.

The following are the most common weighting methods used for access selection in HWN.

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2.3.2.3 Ranking of Candidate Network

There are numerous branches in the MADM algorithm, such as Multiplicative Exponent Weighting (MEW), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Simple Additive Weighting (SAW), Gray Relation Analysis (GRA), ELimination Et Choix Traduisant la REalite (ELECTRE), VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) [75, 76], the main ideas of MADM algorithms commonly adopted in network access selection are presented below, respectively.

i. SAW

SAW is one of the most commonly used MADM algorithms in network access selection because of its simplicity and efficiency. SAW multiplies each decision parameter by its weight, and then sums all the products. Candidate networks are sorted from largest to smallest based on the sum, it has the following definition.

$$S_i^{SAW} = \sum_{j=1}^{n} r_{ij} w_j \tag{2.2}$$

ii. MEW

The divergence between MEW and SAW is that the calculation of MEW for each decision parameter is not the sum of the product of each parameter and the weight, instead, the decision parameters and their weights appear in the form of weighted products, it has the following definition.

$$S_i^{MEW} = \prod_{j=1}^{n} r_{ij}^{w_j} \tag{2.3}$$

iii. GRA

GRA uses the sample data of each decision parameter as its foundation and the gray correlation coefficient to indicate how closely the parameters are related. If the sample data column reflects a similar trend of change between the two parameters, the correlation between them is greater; otherwise, it is smaller.

When using the GRA method for access selection, the optimal value of each decision parameter is first determined and constitutes a reference series $x_0 = (x_0(1), x_0(2), \cdots, x_0(\mathrm{n}))$。

Subsequently, the absolute difference between the sequence of candidate network parameters and the corresponding parameters of the reference series $|x_0(j) - x_i(j)|$, $(j = 1,2,\cdots,n, i = 1,2,\cdots,m)$ is calculated, and the correlation coefficient between each sequence of candidate network parameters and the corresponding parameters of the reference series is calculated as follows.

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$$\zeta_i(\mathrm{j}) = \frac{\min\limits_i \min\limits_j |x_0(j) - x_i(j)| + \rho \max\limits_i \max\limits_j |x_0(j) - x_i(j)|}{|x_0(j) - x_i(j)| + \rho \max\limits_i \max\limits_j |x_0(j) - x_i(j)|} \tag{2.4}$$

In the above equation, $\min\limits_i \min\limits_j |x_0(j) - x_i(j)|$, $\max\limits_i \max\limits_j |x_0(j) - x_i(j)|$ are the two-level minimum and two-level maximum differences, respectively, and the ρ is the resolution factor taken between (0,1), the larger ρ is, the larger the resolution is.

Ultimately, the mean values of the correlation coefficients of each decision parameter and the corresponding elements of the reference series are calculated independently for each candidate network, and the correlation sequence for each candidate network is obtained.

$$S_i^{GRA} = \sum_{j=1}^{n} w_j \zeta_i(j) \qquad (2.5)$$

If the reference number is listed as the best value of each decision parameter, the network with the largest S_i^{GRA} is selected as the access network, otherwise if the reference number is listed as the worst value of each decision parameter, the one with the smallestS_i^{GRA} is selected as the access network.

iv. TOPSIS

The TOPS'S algorithm primarily analyzes the proximity of the access network to the best and worst networks for ranking purposes. The most ideal scenario is when the evaluated candidate network is closest to the best network, and at the same time, the evaluated candidate network is farthest from the worst network. The following is how TOPSIS is formulated:

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$$S_i^{TOPSIS} = \frac{D_i^-}{D_i^+ + D_i^-} \qquad (2.6)$$

In the above equation, $D_i^- = \sqrt{\sum_{j=1}^{n} w_j^2 (r_{ij} - V_j^-)^2}$, $D_i^+ = \sqrt{\sum_{j=1}^{n} w_j^2 (r_{ij} - V_j^+)^2}$, where V_j^- and V_j^+ denote the worst and best values of parameter j in the network, respectively.

Eventually, the network with the largest S_i^{TOPSIS} value is ranked in the order from largest to smallest, and the network with the largest S_i^{TOPSIS} value is the closest to the ideal network.

The main related literature of MADM-based access selection algorithm is analyzed as follows.

A network selection technique was presented by Ahuja et al. [31] for use in a HWN environment that includes UMTS, WLAN, GPRS and WiMAX. It considers the effects of different network attributes such as bandwidth and latency, calculates the weights of the network attributes using the entropy method and adjusts the weights of the attributes according to the needs of different applications, and finally, by TOPSIS method to obtain the scores of each candidate network. Additionally, the literature takes into account the situation of voice, video, and data applications with varied requirements, but overlooks the different preferences of individual applications.

Verma et al. [77] proposed a multi-attribute network access selection algorithm combining GRA and AHP for simultaneously providing high quality services and satisfying contrasting types of user service level protocols. The algorithm used the AHP method to set the relative weights of attributes based on network performance and used the GRA method to rank the candidate networks.

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Zhong et al. [72] proposed a cognitive wireless network access selection algorithm based on MADM. In order to choose the best network, the algorithm combines the MADM and network cross-layer design. It then builds a decision matrix with cross-layer network attribute data (such as throughput, packet loss ratio, price, delay, and jitter), calculates the weight of each attribute under four services using the AHP, and finally ranks the candidate networks using the TOPSIS method.

Yu et al. [60] developed a hybrid MADM, comprising the Fuzzy Analytic Hierarchy Process (FAHP), standard deviation, and GRA network selection algorithm. This approach considers both attribute weight and utility value. The candidate network is chosen as the target network and the switching procedure starts if the candidate network's comprehensive assessment value is higher than the current network and above a certain threshold; otherwise, the user stays on the current network.

Fouladian et al. [78] employed AHP to determine the weights of decision criteria in a converged environment of Vehicular Ad-hoc Network (VANET) and 3G networks and used a modified VIKOR method to make network selection decisions among candidate networks. The algorithm is applied to optimal gateway selection in HWN and improves the performance in terms of average throughput, average latency, and average vertical switch count in sparse vehicle networks.

Miyim et al. [79] proposed a multilayer algorithm for vertical handoff decision by using RSS, bandwidth, and cost as decision parameters, establishing the membership function, and calculating the weight vector using the mean square deviation method, and finally selecting the candidate networks by the MADM method, which is uncomplicated and finds a balance between user preferences, service requirements and networks.

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Table 2.3 demonstrates in detail the comparison of the aforementioned MADM-based access selection algorithms.

The MADM method is applicable to the design of access selection algorithms for multiple decision parameters in the HWN environment, and the method is computationally efficient in calculating the candidate networks without iterations to calculate the results [57]. However, this type of algorithm frequently does not take into account the QoS requirements of different user services when establishing weights for each parameter.

Table 2.3

Comparison of MADM-based Access Selection Algorithms

Ref	MADM methods	Target	Criteria	Advantages	Disadvantages
Ahuja et al. [31]	Entropy +TOPSIS	Evaluate the weight and select the network according to the QoS parameter threshold	bandwidth, delay, loss, price	Different requirements of three applications are considered	The setting of business threshold affects the determination of attribute weight
Verma et al. [77]	AHP +GRA	Calculate the ranking and make network selection according to the attribute weight	bandwidth, jitter, delay, price	The operation result is based on the original data, and the operation is simple and fast	Objective weight of network attribute is not considered
Zhong et al. [72]	AHP +TOPSIS	Calculate the weight of network attributes and calculate the ranking of candidate networks	throughput, delay, jitter, price and packet loss ratio	A cognitive wireless network access selection framework was proposed	The utility of network attribute values for different services is not considered
Yu et al. [60]	FAHP+SD +GRA	The comprehensive evaluation value of each candidate network is calculated through the comprehensive attribute weight and utility value	bandwidth, delay, jitter, loss, error, price	Apply the linear synthesis vector technique to combine three MADM methods	The setting of switching threshold value needs to be further explained
Fouladian et al. [78]	AHP+VIKOR	Selecting the optimum gateway in integrated 3G and VANET network	RSS, direction, cost, speed, delay, throughput, jitter, loss etc.	The parameters are divided into two categories: precise measurement and approximate measurement	There are certain restrictions on the application of the algorithm.
Miyim et al. [79]	fuzzy logic+MADM	Multi-level vertical handoff decision	RSS, bandwidth and cost	Equilibrium between the user preferences, service requirements and networks	The subjective preference of users for decision parameters is not considered

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2.3.3 Utility Theory-based Access Selection Algorithm

Utility refers to the degree to which consumers are satisfied with a product after purchasing it, which is a common concept in economics. Due to personal preferences and the diversity of service requirements, various users have different levels of satisfaction with the same access selection decision parameter value; hence, the utility value can be used to express how satisfied a user is with a given decision parameter. The main idea of the utility theory-based access selection algorithm is to use the utility function to convert the parameters (such as SNR, error, jitter, service price, transmit power) into utility values, the value range of utility value is generally 0 to 1, and then calculate the combined utility value of each candidate network. The utility value of each candidate network is then computed and ranked, and the network with the highest integrated utility value is ultimately connected.

Table 2.4

Utility Function Classification and Mathematical Formula

Utility form	Mathematical formula
Linear	$\mathrm{u}(x) = ax + b$
Logarithm	$\mathrm{u}(x) = a + b\ln(cx + d)$
Exponential	$\mathrm{u}(x) = a + be^{c(x+d)}$
Sigmoid-1	$\mathrm{u}(x) = \frac{(x/a)^b}{c+(x/a)^b}$
Sigmoid-2	$\mathrm{u}(x) = \frac{1}{1 + e^{a(b-x)}}$
Linear piecewise	$\mathrm{u}(x) = \begin{cases} 0 & , x < x_{min} \\ \frac{x - x_{min}}{x_{max} - x_{min}} & , x_{min} \leq x \leq x_{max} \\ 1 & , other \end{cases}$

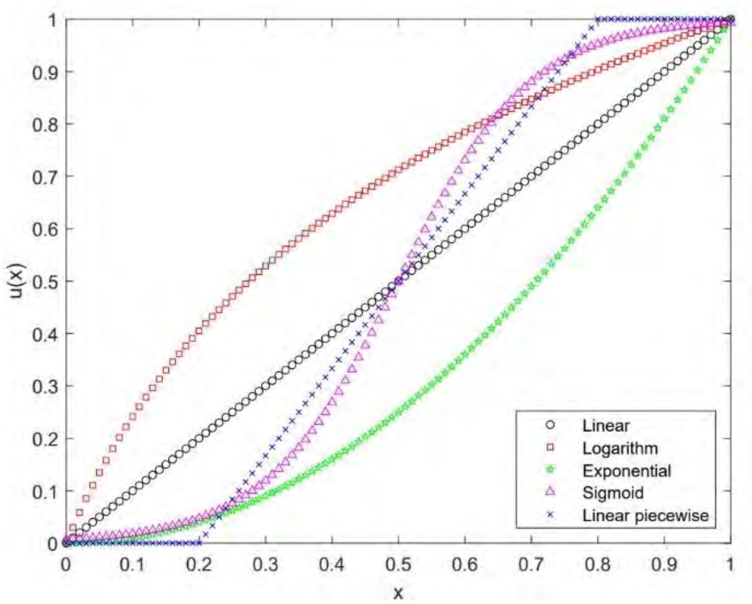

Figure 2.3. Various Utility Function Curves

The types of utility functions commonly used in the access selection algorithm are: linear, logarithm, exponential, and sigmoid functions, as demonstrated in Figure 2.3 and Table 2.4.

The following is an analysis of the primary relevant literature on utility theory-based access selection algorithms.

Goyal et al. [30] modeled the QoS requirements of various network parameters for several sorts of applications (i.e., voice, video, and best-effort applications) using utility functions, used the FAHP to construct a triangular fuzzy number comparison matrix, and proposed a nonlinear fuzzy optimization model for computing the weights of attributes from fuzzy comparison matrices. Using Multiple Attribute Decision Making, the final score for each candidate network is then determined.

Jiang et al. [53] studied the access selection issue related to vehicle-to-infrastructure networking, using energy consumption, signal strength, price, delay and bandwidth as decision parameters to design utility functions, combined with multi-parameter utility theory to create energy-efficient access selection methods. An optimization problem with multiple constraints is used to simulate network selection.

Yan et al. [80] introduced a dynamic imprecise-aware access selection algorithm to address the uncertainty of wireless network status in high-speed train scenario. Fuzzy rules are used to deduce the imprecise statuses, utility functions are created to determine the users' QoS requirements, and the state monitoring module chooses the network.

Wu et al. [34] considered different QoS requirements for voice and streaming services, integrated user preferences, channel state information, cost and network load, constructed utility functions to represent user satisfaction, and adjusted the network access selection scheme from user perspective and network perspective.

The access selection approach proposed by Chamodrakas et al. [54] considers network conditions, quality of service requirements, user preferences, and energy consumption. It also uses multi-parameter utility functions, models various QoS elasticities of various applications, and employs various energy consumption metrics for both non-real-time and real-time applications. Finally, it uses an improved TOPSIS method to solve the candidate network ranking anomaly problem.

An access selection method was stated by Liang et al. [36] that combines service characteristics and user preferences. The algorithm first determines the utility value of each network property depending on the characteristics of various services using utility functions, and then uses the entropy method and FAHP to determine the subjective weight and objective weight of network properties. Finally, both FAHP and MADM are used to determine user preferences and candidate network scores.

The utility function-based network selection techniques discussed above are

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thoroughly compared in Table 2.5.

The utility function-based network access selection algorithm has faster decision speed and lower algorithm complexity, and considers dissimilar business requirements. However, due to the diversity of service types, utility functions need to be designed for each service individually. Furthermore, user requirements and network states are dynamically changing in the real environment, and the utility function, once defined, cannot be adjusted during the whole access selection calculation process, and the flexibility is somewhat limited.

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Table 2.5
Comparison of Access Selection Algorithms Based on Utility Theory

Ref	Utility form	Criteria	Advantages	Disadvantages
Goyal et al. [30]	Sigmoid	bandwidth, delay, jitter	Compared to existing optimization models, the weights from this algorithm are more consistent.	The nonlinear fuzzy optimization model increases the complexity of the algorithm
	Linear	delay, jitter, error, cost		
Jiang et al. [53]	Sigmoid	energy efficiency, RSS, delay, bandwidth	The utility functions are created to characterize the network performance and users' preferences	Modeling network selection as a multi constraint optimization problem limits the application of the algorithm.
	Linear	cost		
Yan et al. [80]	Linear piecewise	bandwidth, RSS, SNR, delay, jitter, loss	Combining fuzzy logic reasoning can better deal with the network selection in the state of imprecise values	The type of utility function is only linear function, and utility function is not defined for different attributes according to different services types
Wu et al. [34]	Linear piecewise	rate, channel gain	Considering the speed requirements of voice services and streaming media services, the load between networks can be adjusted	The calculation of attribute weight under different services is not described in detail
	Logarithm	rate		
	Exponential	price		
Chamodrakas et al. [54]	Sigmoid	bandwidth, delay	The algorithm strikes a compromise between network performance and energy consumption in access selection	How to reduce ping pong effect in access handover is not considered
	Linear	energy consumption		
Liang et al. [36]	Sigmoid	bandwidth, delay	Three different businesses are considered, as well as subjective and objective weights	The setting of switching threshold directly affects the switching frequency between networks
	Exponential	bandwidth,		
	Logarithm	jitter		
	Linear	jitter, loss		
	Linear piecewise	price		

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2.3.4 Fuzzy Logic-based Access Selection Algorithm

The theory of fuzzy logic originated from a fuzzy set theory different from traditional mathematics proposed by Professor L.A. Zedeh in 1965 [81], which laid the foundation of fuzzy set theory and application. In 1974, by utilizing fuzzy logic theory, Professor Mamdani of the United Kingdom realized the earliest steam engine test control [82], and obtained better results than the conventional control method, marking the beginning of industrial control with fuzzy logic. In 1985, Tomohiro.Takagi and Michio.Sugeno of Japan proposed the T-S fuzzy model [83], which provides an accurate calculation method for the fuzzy model identification of the system.

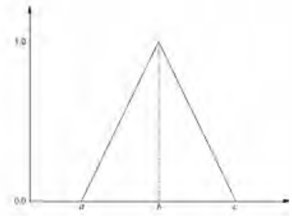
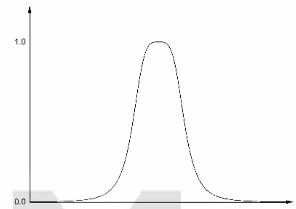
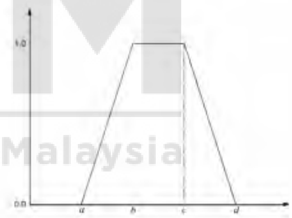
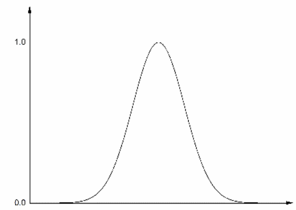
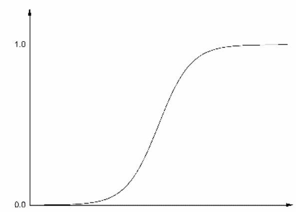
In the calculation process of access selection, there are often some fuzzy information that is difficult to quantify. For instance, if a candidate network has high bandwidth, low latency and low packet loss ratio, then we can assume that the candidate network has a high score; on the contrary, if a candidate network has low bandwidth, medium latency and high packet loss ratio, then we may assume that the candidate network has a low score. Hence, when making access selection decision, we can employ a fuzzy logic-based calculating technique [84-86].

The primary goal of this algorithm is to first fuzzify each network parameter and generate an input fuzzy set, which generates a specific output fuzzy set through fuzzy rules and fuzzy inference, and finally obtains the accurate score sorting of the candidate network by defuzzification. The key to fuzzy logic theory lies in the rational definition of fuzzy sets and fuzzy inference.

For fuzzy sets, Professor Zadeh defines it as: Given a domain U, U to [0,1] closed interval to any mapping $\mu_A: U \to [0,1]$ determines a fuzzy set A of U, μ_A is called the membership function of fuzzy set A, which reflects the extent to which elements x in the fuzzy set belong to the set.

Table 2.6

Membership Function and Its Shape

Membership function	**Functional form**	**Function curve**
triangular membership function	$f(x)=\begin{cases}0 & ,x\le a\\ \dfrac{x-a}{b-a} & ,a\le x\le b\\ \dfrac{c-x}{c-b} & ,b\le x\le c\\ 0 & ,x\ge c\end{cases}$	
Bell-shaped membership function	$f(x)=\dfrac{1}{1+\left\lvert\dfrac{x-c}{a}\right\rvert^{2b}}$	
trapezoidal membership function	$f(x)=\begin{cases}0 & ,x\le a\\ \dfrac{x-a}{b-a} & ,a\le x\le b\\ 1 & ,b\le x\le c\\ \dfrac{d-x}{d-c} & ,c\le x\le d\\ 0 & ,x\ge d\end{cases}$	
Gaussian membership function	$f(x)=e^{-\frac{(x-c)^2}{2\sigma^2}}$	
sigmoid membership function	$f(x)=\dfrac{1}{1+e^{-a(x-c)}}$	

Additionally, in order to create fuzzy sets from the input terms' values, the membership function should be used for the conversion. The membership functions that are most

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frequently employed are the triangular membership function, bell-shaped membership function, trapezoidal membership function, gaussian membership function, etc. The mathematical model and shape of membership functions are shown in Table 2.6.

In fuzzy logic theory, fuzzy logic rules are essentially fuzzy implication relations. In fuzzy logic, there are many methods to define a fuzzy implication. The most commonly used type of fuzzy implication is the generalized affirmative inference method, that is:

Input: if x is A'

Premise: if x is A, then y is B

Conclusion: y is B'

For the fuzzy premise "if x is A, then y is B", it represents the fuzzy implication relationship $A \rightarrow B$ between the fuzzy languages A and B. The most used fuzzy implication relation operation method is the minimum operation. Conclusion B' is inferred from the combination of fuzzy set A' and fuzzy implication relation $A \rightarrow B$, thus, it is possible to derive the following fuzzy inference relationship:

$$B' = A' \circ (A \rightarrow B) = A' \circ R \tag{2.7}$$

For the input and prerequisite of the ambiguous condition, statements are connected by "and", as in:

Input: if x is $A'$and y is B'

Prerequisite: if x is A and Y is B, then z is C

Conclusion: z is C'

The fuzzy premise "x is A and y is B" can be regarded as a fuzzy set on the direct product space $X \times Y$. Its membership function is $\mu_{A\times B}(x, y) = \min\{\mu_A(x), \mu_B(y)\}$. This is a fuzzy implication relation which can be recorded as $R = A \times B \to C = A \times B \times C$. Therefore, the conclusion that z is C'can be obtained from the following fuzzy inference relations:

$$C' = (A' \times B') \circ (A \times B \to C) = (A' \times B') \circ R \tag{2.8}$$

For fuzzy conditional statements connected by "also", the format is:

Input: if x is A' and y is B'

Premise 1: if x is A_1 and y is B_1, then z is C_1

Also premise 2: if x is A_2 and y is B_2, then z is C_2

......

Also premise n: if x is A_n and y is B_n, then z is C_n

Conclusion: z is C'

Suppose the fuzzy implication relation R_i of the *i*-th rule "if x is A_i and y is B_i, then z is C_i" is $R_i = A_i \times B_i \to C_i$ is the fuzzy implication relation defined on $X \times Y \times Z$, then the total fuzzy implication of the *n* fuzzy control rules is:

$$R = \bigcup_{i=1}^{n} R_i \tag{2.9}$$

According to the fuzzy set C', the output fuzzy variable z is expressed as follows:

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$$C' = (A' \times B') \circ R \tag{2.10}$$

The main relevant literature on access selection algorithms based on fuzzy logic theory is analyzed as follows.

Thumthawatworn et al. [51] proposed a modular and adaptive design concept for a fuzzy logic-based access selection algorithm. This concept leads to high algorithm execution time when considering a large number of decision parameters. They addressed this by dividing the decision parameters into multiple input groups that are computed by different fuzzy inference engines. The proposed design reduces the number of fuzzy rules and the execution time of the algorithm while enhancing the network selection capability.

Ali et al. [87] proposed an algorithm for channel selection and switching, which is based on two fuzzy logic controllers. The controller operates under five performance parameters. The first fuzzy logic controller is used to reduce the frequency of channel switching, while the second one is used to choose the best channel from the list of available channels.

In addition, Ahuja et al. [88] suggested a network selection algorithm integrating fuzzy logic with utility function. The algorithm uses a utility function to calculate the utility value of RSS, bit rate, SNR, throughput, and BER. It then uses the particle swarm optimization (PSO) method to determine the weight. Furthermore, it uses a fuzzy logic system to determine the output results, reducing the number of unnecessary network handoffs.

Khan et al. [55] combined fuzzy logic and MADM to design a vertical handoff scheme for HWN. The scheme consists of three steps: the first phase focuses on the handover triggering approach, while the second phase eliminates unsuitable candidate networks using a fuzzy system, and the third phase ranks the remaining candidate networks using the TOPSIS method. To choose the optimum network, the scheme takes into account a number of factors, including BER, latency, jitter, packet loss, communication cost, response time, and network load.

Kustiawan et al. [89] proposed a channel switching method in HWN integrating Kalman filtering and fuzzy logic. The method used Kalman filtering for channel equalization in the channel propagation model and Mamdani fuzzy logic for handoff decision.

Mehbodniya et al. [90] proposed an access selection algorithm combining fuzzy logic and MADM for HWN. The algorithm designed two modules to evaluate the necessity of switching and select the target network. Module one uses the fuzzy logic controller to evaluate the necessity of switching, and the second module is based on fuzzy VIKOR to calculate the ranking of candidate networks. The algorithm improves end-user satisfaction.

Table 2.7 provides a specific comparison of the above fuzzy logic-based access selection algorithms.

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Table 2.7

Comparison of Access Selection Algorithms Based on Fuzzy Logic

Ref	Algorithm model	Parameter	Membership function	Advantages	Disadvantages
Thumthawatworn et al. [51]	multiple fuzzy inference engine	rate, delay, jitter, loss, battery, price	trapezoidal, triangular (Low, Medium–Low, Medium, Medium–High, High)	The grouping of decision parameters effectively reduces the number of fuzzy rules in the case of multiple decision parameters	The basis for grouping decision parameters is not specified in detail
ALI et al. [87]	multiple fuzzy inference engine	temperature, power, SINR, rank, range	triangular (Low, Medium, High)	Reduced switching frequency on the premise of choosing the optimal connection	Different business types are not considered
Ahuja et al. [88]	utility theory + fuzzy logic	RSS, rate, SNR, throughput, error	triangular (Low, Medium, High)	Considering quality of service and user satisfaction	The calculation of weights leads to an increase in the complexity of the algorithm
Khan et al. [55]	fuzzy logic +MADM	cost, load, response time, delay, jitter, error, loss	triangular (Low, Medium, High)	The algorithm considers the calculation of the Handover triggering phase and the network selection phase	Too many input parameters lead to increased number of fuzzy rules
Kustiawan et al. [89]	Kalman filter + fuzzy logic	RSS, data rate, velocity, traffic load	Gaussian (Low, Medium, High)	Ability to provide more accurate estimates of input data	Different business types are not considered
Mehbodniya et al. [90]	fuzzy logic + VIKOR	RSS, delay, jitter, loss, throughput, speed, distance, load, security, cost	triangular (Very low, Low, Medium, High, Very Hight, Excellent)	The input decision parameters are classified and calculated by 3 fuzzy logic controllers	The setting of the size of the switching threshold will directly affect the result of the network selection

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The advantages of the fuzzy logic-based access selection algorithm are that its reasoning approach is similar to human thought, the rules formulated are easily understood, and the algorithm is more effective when the number of input items is small. Nonetheless, as the number of input items increases, causing a dramatic increase in the number of rules of the fuzzy inference rule base, both the definition and computation of the rules take longer.

2.3.5 Game Theory-based Access Selection Algorithm

In HWN, there is a corresponding impact on the user and the network when a user connects to the network, so the Game Theory model can be applied to research access selection [91]. Player, strategy, and payoff are the three crucial components of the game model [92].

In the access selection of HWN, the players are usually users or networks, and the set of players can be represented as $\Gamma = \{1,2,\cdots,\mathrm{n}\}$, all of whom aim to maximize their utility by choosing a strategy [93]. Moreover, according to the two parties involved in the game, it can be divided into inter-user game, inter-network game, and inter-user-network game.

A game strategy in access selection represents a user's connection to a network, or a network's allocation of certain resources to a user. It specifies the conduct of the user or network during access. We can use s_i to denote a strategy of player i, and $S_i = \{s_i\}$ to denote the set or strategy space of all selectable strategies of player i. In a game cycle, a player can select a certain strategy from the set of strategies. If n players each choose a strategy, the n-dimensional vector $\mathrm{S} = (s_1, s_2, \cdots, s_i, \cdots, s_n)$ is called a strategy combination.

Payoff, also called utility, in network access selection, the user or network can design a utility function to evaluate the benefit based on each decision parameter (e.g., bandwidth, delay, price, energy consumption). The goal of each player is to choose a certain strategy to maximize its utility, usually denoted by u_i the utility value obtained by player i. Then under a strategy combination, the utility of each participant in a strategy combination can be expressed as: $u_i = u_i(s_1, s_2, \cdots, s_n), i = 1,2, \cdots, n$。 Therefore, in a game with n participants, the strategy space of participants is $S_1, S_2, \cdots, S_n$ and the utility function is $u_1, u_2, \cdots, u_n$, then the game can be expressed as: $\mathrm{G} = \{S_1, S_2, \cdots, S_n; u_1, u_2, \cdots, u_n\}$。

Moreover, game theory can be subdivided into cooperative and non-cooperative games based on the interactions between the game's two players. Cooperative games ensure that the benefits of at least one player are increased in network access selection without compromising the benefits of other players, thereby increasing the overall benefits of HWN. The cooperative game emphasizes fairness and overall optimal decision making, and its solutions (e.g., Nash Bargaining Solution) generally have Pareto Optimum. In a non-cooperative game, players choose the strategy with the greatest benefit to themselves, regardless of the benefits of other players. The non-cooperative game emphasizes the optimal decision of the individual players, and its solution is the Nash Equilibrium. Nash Equilibrium is a game with n players, if for each player $i (i = 1,2, \cdots, n)$， s_i^* is the optimal strategy of the strategy $(s_1^*, \cdots, s_{i-1}^*, s_{i+1}^*, \cdots, s_n^*)$ chosen for the other $n-1$ players, i.e.:

$$u_i(s_1^*, \cdots, s_{i-1}^*, s_i^*, s_{i+1}^*, \cdots, s_n^*) \geq u_i(s_1^*, \cdots, s_{i-1}^*, s_i, s_{i+1}^*, \cdots, s_n^*), \forall s_i \in S_i \quad (2.20)$$

That is, s_i^* is the solution of the optimal problem

$\max_{s_i \in S_i} u_i(s_1^*, \cdots, s_{i-1}^*, s_i, s_{i+1}^*, \cdots, s_n^*)$, $i = 1,2, \cdots, n$, then the strategy combination $s^* = (s_1^*, \cdots, s_{i-1}^*, s_i^*, s_{i+1}^*, \cdots, s_n^*)$ is the Nash Equilibrium of the game. There can be more than one Nash Equilibrium in the game and it is not unique.

In addition, the commonly used game models in network access selection are Prisoners Dilemma, Auction Game, Bayesian Game, Bargaining Game, Multi-Leader-Follower Game, Bankruptcy Game, Stackelberg Game, Evolutionary Game) [94].

The relevant literature analysis of access selection algorithms based on game theory is as follows.

Luong et al. [95] studied a user-centric dynamic network service selection algorithm that integrates different resources such as transmit power and intelligent reflecting surface (IRS) resources and proposed an evolutionary game model. It is important to note that users modify their choice of network and services during the gaming process depending on their respective business needs.

Goyal et al. [96] proposed a group vertical handover algorithm based on non-cooperative games, which uses different network attributes and user preferences as game strategies. Under Nash equilibrium, group mobile users will switch to the best available wireless network. The algorithm maximizes both the revenue of the candidate network and the satisfaction of each group of mobile users.

Ma et al. [58] proposed an evolutionary game-based network selection algorithm, which first uses AHP to examine user preferences and service requirements and then uses SAW method and utility function to construct network attributes and utility of available capacity. The algorithm improves the average user satisfaction and energy efficiency, and reduces the average delay and packet loss ratio, with increasing number of users.

Furthermore, Chen et al. [97] constructed the relationship between networks and users in heterogeneous systems based on a game model, and used a unified quantitative model to evaluate the effectiveness of access selection. Finally, they designed a network selection algorithm to maximize user performance-cost-ratio.

Niyato et al. [98] divided users into different regions of the HWN environment into different groups. These user groups were modeled as an evolutionary game competing for shared bandwidth in the available wireless networks. Two algorithms for network selection are proposed using evolutionary game theory, namely reinforcement learning and population evolution.

Additionally, Wang et al. [99] researched the user-centric network selection issue in ultra-dense HWN in order to accomplish quick and efficient network selection. They then suggested a model-driven learning strategy that blends game theory and machine learning.

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The comparison of the above game theory-based access selection algorithms is demonstrated in Table 2.8.

Table 2.8
Comparison of Access Selection Algorithms Based on Game Theory

Ref.	Game Type	Game Model	Players	Strategies	Payoffs	Advantages	Disadvantages
Luong et al. [95]	Cooperative	Evolutionary Game	Users vs. Users	Users select different network resources	Utility based on the prices and network services	Balance energy consumption and price	The overall performance of the network is not optimized
Goyal et al. [96]	Non-Cooperative	Two Player Game	Users vs. Networks	User switches to the best candidate network	Improve network revenue and user satisfaction	Can meet the minimum needs of the group user's business	No specific method for calculating user preferences is given
Ma et al. [58]	Non-Cooperative	Evolutionary Game	Users vs. Users	The selection of the candidate network	The net utility obtained by selecting a network	User preference is considered and network load balancing is implemented	The detailed payment calculation process is not given according to different business characteristics
Chen et al. [97]	Non-Cooperative	Bertrand game	Networks vs. Networks	Setting access service prices	Network revenue of service providers and performance-cost ratio of users	Obtain Nash equilibrium price and coalition price under non-cooperative and cooperative game models	The dynamic characteristics of price competition are not considered
	Cooperative	Bertrand game	Users vs. Networks	Pricing uniformly choosing any network			
Niyato et al. [98]	Non-Cooperative	Evolutionary Game	Users vs. Users	The selection of a wireless access network	The user's satisfaction on achievable throughput	Centralized and distributed network selection algorithms are realized	It is not explained how to group users in different service areas according to service class
WANG et al. [99]	Non-Cooperative	Evolutionary Game	Users vs. Users	The choice of serve nodes	The throughput utility function of terminal connected to the serve node	Avoid the infinite oscillation of the network selection and guarantee the convergence	Does not consider the impact of more different network attributes on users

The network access selection algorithm based on game theory has high fairness and accuracy when multiple users are selecting networks at the same time. The limitation of this type of algorithm is mainly the assumption that all players (i.e., users or networks) are reasonable and compete for their own benefit, but this tends to impair the overall performance of HWN, and, in order to achieve the Nash equilibrium convergence of different plays, leads to a higher complexity of the algorithm, which consumes more computation time, and only one user's network selection result can be derived in one game cycle, which is less efficient for network selection.

2.3.6 Neural Network-based Access Selection Algorithm

Neural network is a biomimetic model based on neural cells, which is used to study artificial intelligence mechanisms by mathematizing neurons. In addition, fuzzy logic can be introduced into artificial neural networks, i.e., fuzzy logic is introduced into the input, hidden, or output layers of artificial neural networks, and the explanatory power and learning speed of the system are enhanced by using fuzzy logic [100]. In the following, we illustrate the computational approach of fuzzy neural networks in HWN access selection using the fuzzy neural network structure as an example [101].

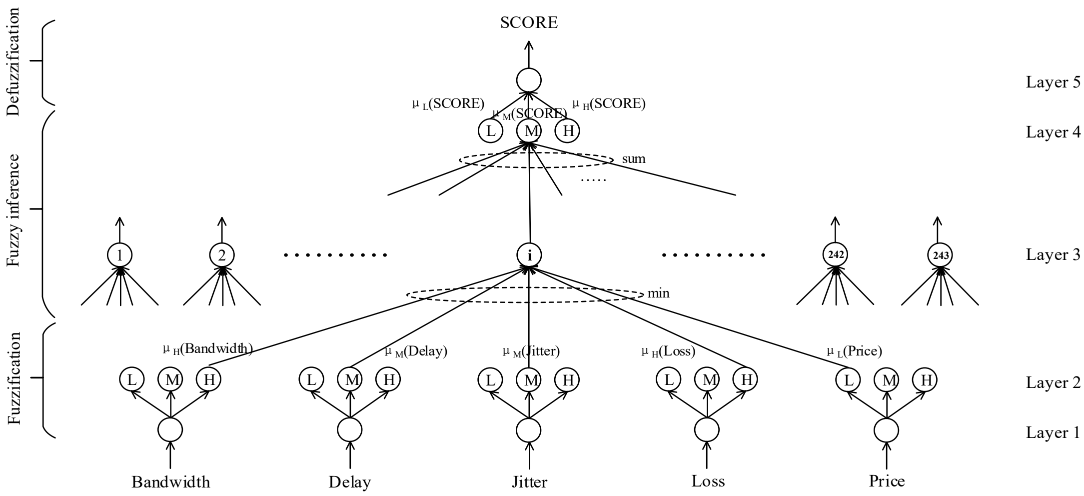

Figure 2.4. Network Selection Structure Based on Fuzzy Neural Network

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The specific structure of the neuron node in Figure 2.4 is demonstrated in Figure 2.5. Let node i in layer k has a total of j input data, then the input of this node can be expressed as $I_i^{(k)} = f_i^{(k)}(x_{i,1}^{(k)}, x_{i,2}^{(k)}, \cdots, x_{i,j}^{(k)})$, where $f_i^{(k)}$ represents the input data processing function, which processes the input data and then outputs it through the activation function $g_i^{(k)}$, i.e., the output value is $O_i^{(k)} = g_i^{(k)}(I_i^{(k)})$.

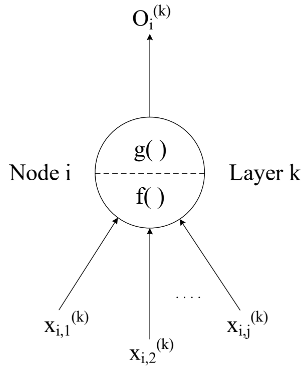

Figure 2.5. Basic Structure of a Single Neuron Node

In Figure 2.4, Layer 1 is the input layer, and its primary function is to convert the collected values of each network attribute (e.g., bandwidth, jitter, delay) into normalized values, which are then used as inputs to the neural network. Layer 1 has only one input per node, and the total number of nodes in this layer is equal to the total number of network attributes. The input and output of node i in this layer can be expressed as:

$$I_i^{(1)} = f_i^{(1)}\left(x_{i,j}^{(1)}\right) = x_{i,j}^{(1)} \tag{2.11}$$

$$O_i^{(1)} = g_i^{(1)}\left(I_i^{(1)}\right) = x_{i,j}^{(1)} \tag{2.12}$$

Layer 2 is the fuzzification layer. This layer's primary function is to conduct fuzzification, converting the input exact quantities into fuzzified quantities and mapping them into fuzzy sets, in general, fuzzy sets can be represented by low, medium, and high. Each node in layer 2 has a single input and is responsible for calculating the membership function for each input value that belongs to the corresponding fuzzy set. Since the Gaussian-type function is easy to derivate and is more efficient in the learning phase, it is generally used as the membership function. The inputs and outputs of node i in layer 2 are obtained as:

$$I_i^{(2)} = f_i^{(2)}\left(x_{i,j}^{(2)}\right) = -\frac{\left(x_{i,j}^{(2)} - c_i^{(2)}\right)^2}{\left(\sigma_i^{(2)}\right)^2} \tag{2.13}$$

$$O_i^{(2)} = g_i^{(2)}\left(I_i^{(2)}\right) = e^{I_i^{(2)}} = e^{-\frac{\left(x_{i,j}^{(2)} - c_i^{(2)}\right)^2}{\left(\sigma_i^{(2)}\right)^2}} \tag{2.14}$$

The $c_i^{(2)}$ and $\sigma_i^{(2)}$ in the above equation represent, respectively, the mean and variance (Gaussian-type membership function) of node i in layer two, and s is the total number of fuzzy sets of all nodes in that layer.

Layer 3 is the fuzzy rule layer, there are exactly as many nodes in this layer as there are rules in the fuzzy rule base, every node corresponds to a fuzzy rule, the number of input data of each node is equal to the number of nodes in layer 1. The fuzzy AND operation is used for all input data of the same fuzzy rule, and the commonly used fuzzy AND operation is minimum operation. Only the equivalent value of the input function is transmitted by the activation function of each node in this layer. The inputs and outputs of node i in layer 3 can be expressed as follows, respectively:

$$I_i^{(3)} = f_i^{(3)}\left(x_{i,j}^{(3)}\right) = \min\left(x_{i,j}^{(3)}\right) \tag{2.15}$$

$$O_i^{(3)} = g_i^{(3)}\left(I_i^{(3)}\right) = \min\left(x_{i,j}^{(3)}\right) \tag{2.16}$$

$x_{i,j}^{(3)}$ in the above equation denotes the jth input data of node i in layer 3, which is equal to the output data of node j in layer 2 to which node i is connected.

Layer 4 is the fuzzy rule inference layer. Here, all rules with the same conclusion in layer 3 point to the same node in layer 4. A fuzzy OR operation is executed for input data pointing to the same node, with bounded sum or union being the most common fuzzy OR operations. Since there is only one output linguistic variable (i.e., the score of the candidate network) in layer 5, if that variable has three fuzzy sets (such as low, medium, and high), then there are a total of three nodes. The inputs and outputs of node i in layer 4 can be expressed, respectively as follows:

$$I_i^{(4)} = f_i^{(4)}\left(x_{i,j}^{(4)}\right) = \sum_{j \in C_i} x_{i,j}^{(4)} \tag{2.17}$$

$$O_i^{(4)} = g_i^{(4)}\left(I_i^{(4)}\right) = \min\left(1, I_i^{(4)}\right) \tag{2.18}$$

C_i in the above equation denotes the set of nodes in layer 3 that are connected to node i in layer 4.

Layer 5 is the output layer, which has only one node, and its main function is to perform defuzzification operation to get the exact score of the candidate network. The commonly used defuzzification calculation methods are the MOM method and the COA method. Therefore, the input and output of the nodes in layer 5 can be expressed as follows.

$$I_i^{(5)} = f_i^{(5)}\left(x_{i,j}^{(5)}\right) = \sum_{j \in T_i} c_j^{(5)} \sigma_j^{(5)} x_{i,j}^{(5)} \tag{2.19}$$

$$O_i^{(5)} = g_i^{(5)}\left(I_i^{(5)}\right) = \frac{I_i^{(5)}}{\sum_{j\in T_i}\sigma_j^{(5)}x_{i,j}^{(5)}} = \frac{\sum_{j\in T_i}c_j^{(5)}\sigma_j^{(5)}x_{i,j}^{(5)}}{\sum_{j\in T_i}\sigma_j^{(5)}x_{i,j}^{(5)}} \tag{2.20}$$

The T_i, $c_j^{(5)}$ and $\sigma_j^{(5)}$ in the above equation are the set of nodes in layer 4 connected to node i in layer 5, the mean of the Gaussian function, and the variance of the Gaussian function.

After obtaining the score of the candidate network, it is necessary to compare this score with the user's expected score of this network and calculate the error value between them, and the commonly used error calculation function is the mean-square error (MSE). The error values are used to solve the adjusted values of the mean and variance of the membership functions (i.e., $\Delta\sigma_i^{(2)}$、$\Delta c_i^{(2)}$、$\Delta\sigma_j^{(5)}$、$\Delta c_j^{(5)}$) in the fuzzification layer (i.e., layer 2) and the defuzzification layer (i.e., layer 5) [102]. The adjustment values are generally solved using Gradient Descent.

The main relevant literature on neural network-based access selection algorithms is analyzed as follows.

Calhan et al. [103] proposed a handoff decision algorithm based on artificial neural network, which uses data rate, cost, and RSS as input decision parameters to determine whether it is necessary to switch to other networks and to select the best access network among the candidate networks. The algorithm is capable of decreasing both the number of handoffs and the handoff delay.

Chen et al. [104] proposed a fuzzy Q-learning based access control method for multimedia traffic in heterogeneous networks consisting of WCDMA and WLAN. The neural-fuzzy inference system (NFIS) admissibility estimator, NFIS dwelling estimator and decision maker make up the fuzzy Q-learning admission control system. The admissibility estimator is responsible for calculating the QoS demand and access cost of each subnet that can support the access service, the dwelling estimator is responsible for calculating the Doppler shift and power intensity, and the decision maker uses the exceptionally large minima theorem to determine the most suitable subnet for user access requests.

In a HWN environment, Giupponi et al. [105] created a framework for joint radio resource management (JRRM). In their research, a fuzzy neural JRRM algorithm with three disparate radio access technologies (RAT) is proposed. The first step of this algorithm involves different combinations of three available RATs, while the next step helps to choose the most suitable RATs and assign the appropriate bit rate to each user.

2.3.7 Other Access Selection Algorithms and Comparison

In addition to the various access selection algorithm models mentioned above, some literature uses Markov decision process (MDP) [106, 107], optimization method models [108-110] for network access selection.

In order to improve the service quality of high priority services, Goudarzi et al. [111] identified the optimal decision set and evaluated the QoS of each connection by constructing a reward function. Then, a vertical switching algorithm was designed based on a combination of MDP and genetic algorithm (GA), which improved the overall return and reduced the switching frequency.

Khloussy et al. [112] advanced an MDP-based network selection method, where the goal is to maximize the operator's revenue is the goal, while considering the QoS requirements and charges for different services and providing preferential treatment to users with higher charges. In addition, the spatial distribution of base stations, access points (AP) and subscribers are considered for traffic modeling.

Navarro et al. [113] modeled vertical handoff in a heterogeneous centerless network as an MDP, where users benefit from a link reward mechanism linked to QoS via the connection and the signaling overhead cost function incurred during vertical handoff is considered. The goal of the vertical handoff policy is to maximize the total expected reward for each connection.

Lee et al. [114] proposed an optimized vertical handover method for HWN, which not only balances the load of each base station or access point, but maximizes the battery life of mobile terminal nodes.

Choi et al. [115] examined the mobile user's air interface and band selection, as well as the links' power distribution issue, and suggested a distributed joint allocation algorithm, which analyzes and solves the bandwidth and power allocation problems in multi-link access with the objective of maximizing the total system capacity.

In summary, contrasting mathematical models used in access selection have different characteristics, here we compared the objectives, decision speed, complexity, accuracy, and effectiveness of each model, as demonstrated in Table 2.9.

Table 2.9

Comparison of Access Selection Algorithm Models

	MADM	Utility theory	Fuzzy Logic	Game theory	Neural network	Markov chains	Optimization method
Objective	Multi-attribute combination	Utility evaluation	Fuzzy processing	Inter-entity balance	Minimum error	Continuous decision making	Integer programming
Decision speed	Fast	Fast	Fast	Medium	Slow	Medium	Slow
Complexity	Low	Low	Low	High	High	Medium	High
Accuracy	High	Medium	Medium	High	Medium	Medium	High
Effectiveness	High	Medium	Medium	High	High	Medium	Medium
User-centric	Yes	Yes	Yes	No	Yes	Yes	No

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2.4 Problems, Challenges, and Future Trends of Access Selection

2.4.1 Existing problems

Although there is a lot of literature on the access selection problem of HWN, there are many problems to be solved and areas to be optimized in the access selection algorithm, and in general, most of the algorithms still have the following deficiencies [116].

i. Although the access selection algorithm on the basis of a single decision parameter has low computational complexity, the effectiveness is poor, and does not allow the user to select the most suitable network. In addition, some literature tries to add all decision parameters into consideration during the algorithm design, but it leads to a sharp increase in computational complexity, which is not suitable for the practical application environment.

ii. Some algorithms select the best-performing network from a set of candidate networks for access, hoping to connect users to the network with the best overall performance. However, the variety of user services, each type of service has different requirements for each network attribute. For instance, some services need real-time guarantee, some services need high bandwidth guarantee, and some services want lower service prices. Therefore, when designing the access selection algorithm, we should take into account not only the overall performance of the network, but also the characteristics of the different services, and allow users access to the best network based on the service characteristics [117].

iii. Access selection algorithms do not take user preferences into account in the design process. With the continuous development of various wireless network technologies and the expansion of user base, different users often have exceptionally different preferences and habits, and most access selection algorithms do not take into account the subjective preferences of users for specific parameters and networks, and thus cannot improve the quality of the user experience [118, 119].

2.4.2 Challenges and Future Trends

With the emergence of various new technologies, the communication systems maintained by network operators will be restricted in many ways, such as network planning, total spectrum, policy and energy consumption requirements. At the same time, the performance of intelligent terminals is constantly improving, and the diversification and personalization of users also put forward higher requirements for communication systems. The service constraints and user experience quality provided by various networks are often interdependent, and need to be balanced in network design, resource allocation, user management, and service level. The challenges faced the development of HWN are as follows:

i. Continuous evolution of network architecture

Future wireless network development will be ongoing, particularly as 5G networks continue to evolve and mature, HWN will develop toward the architecture of ultra-dense, multi-level and heterogeneous hybrid networks. There will be more wireless access points of different nature and types in the system. These access points include macro base station, micro base station, WiFi access point, roadside unit base station of vehicular network, and radio frequency unit of narrowband Internet of Things, and in order to provide access services to a growing number of users, the deployment of these access points will become more and more intensive to meet the increasingly high QoS requirements of user services [120]. In addition, considering the energy consumption, the opening and closing of these access points make the network topology no longer a traditional hexagonal honeycomb, but a randomly deployed, amorphous and irregular shape. Therefore, under this wireless network architecture, the connection mode between users and access points has also changed, which can no longer be based on distance and received signal strength. The evolving network architecture brings new challenges to the connection between users and these amorphous access points [121, 122].

ii. Increasing mobile data traffic

Research data and statistics forecast that the total global mobile data traffic has increased 4,000 times in the past decade. In the future, from now until the end of 2023, the total global mobile data traffic will increase rapidly by more than 42% Compound Annual Growth Rate (CAGR). By the end of 2023, the total monthly mobile data traffic will be close to 110 EB. At present, the data traffic generated by mobile user smartphones accounts for about 85% of the total data traffic. Looking ahead, the data traffic generated by smartphones will continue to increase. It is expected to increase by a factor of 9 during the forecast period. By the end of 2023, nearly 95% of the mobile data traffic will come from smartphones. In order to meet the increasing data traffic, network service providers are increasing more base stations and wireless network access points in areas with high data demand to improve network capacity and reduce network congestion. Therefore, how to deal with the increasing data traffic is a challenge for future HWN [123, 124].

iii. The growth and diversification of user service requirements

With the rapid development of electronic hardware technology, user terminal equipment has changed from traditional analog telephone to digital telephone to today's multifunctional smartphone. In addition, the application of a series of intelligent hardware, such as tablet computer, smart portable terminal, wearable devices, has made it more convenient for users to connect to network services [125]. Therefore, personalized and diversified user application services are constantly surging. Nowadays, user services are also developing from traditional voice and short message services to instant messaging, mobile shopping, interactive games, location services, video chat, traffic navigation, health diagnosis and other services. Each service has different service characteristics and service requirements [126]. How to provide better services for increasing service types in complex heterogeneous network environment is another challenge for future HWN.

Therefore, as HWN evolve towards ultra-dense networking with multi-service and multiple QoS requirements, how to design a multi-criteria access selection mechanism to meet service characteristics and different user preferences, and improve the quality of user experience is a problem to be solved [127, 128].

2.5 Comparison of Existing Work

In this research, the access selection mechanism is designed by integrating utility theory, FAHP, fuzzy logic, and MADM. In the process of mechanism design, the considerations include various service characteristics, objective and subjective weights, network attributes, and user preferences. Even if some other works of literature currently have numerous approaches to designing access selection algorithm, however, as far as we know, there are no other access selection mechanisms designed by other literature that integrate these methods at the same time like this research. Most existing access selection mechanisms either consider only a single criterion, or do not take into account different types of service characteristics, or do not take into account the user preferences. Therefore, the primary improvements and features of this research are the proposed system, which provides a more thorough mechanism to choose the best network for users.

The comparison between the proposed mechanism and existing work are shown in Table 2.10.

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Table 2.10

Comparison of Existing Work

Literature	Method	Aims	Decision criteria	Performance metrics	Summary
[30]	Utility function+ FAHP+ MADM	Perform network selection considering service characterizations	**Network Attributes:** bandwidth, delay, jitter, bit error ratio, price **Services:** voice, video and best effort **User Preference:** Subjective weights of various network attributes under different applications	1. Final scores of candidate networks	**Advantages:** Considering voice, video and best-effort applications, the weight calculation method is more reasonable **Disadvantages:** Calculation of user preferences not considered
[31]	Entropy +TOPSIS	Select the network according to the QoS parameter threshold	**Network Attributes:** bandwidth, delay, loss, price **Services:** voice, video and data **User Preference:** no	1. Optimal network selected for different services 2. Effects of the network attribute on selection 3. Sensitivity of network selection	**Advantages:** Different requirements of three applications are considered **Disadvantages:** Subjective weight and user preference are not considered
[59]	AHP + TOPSIS	Design of Context-aware Multi-attribute access selection approach	**Network Attributes:** RSS, bandwidth, delay, jitter, loss, speed **Services:** background, conversational,	1. Number of handovers, 2. Ranking abnormality	**Advantages:** The system model considers the network environment, input criteria, and other factors **Disadvantages:**

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			interactive, and streaming **User Preference:** Subjective weights were calculated		The user preference value is not quantified
[36]	Utility function + FAHP + Entropy + MADM	Design a multi-attribute access selection algorithm	**Network Attributes:** bandwidth, delay, jitter, loss, price **Services:** voice, video and data **User Preference:** The subjective weight and the value of preference for candidate networks are considered	1. Final scores of candidate networks, 2. Number of network selection of candidate networks, 3. Number of network handovers	**Advantages:** The role of different network attributes in various services is considered **Disadvantages:** User preferences cannot well reflect the fuzzy information of user preferences, and no performance metrics for evaluating the user experience.
[80]	Utility function + Fuzzy Logic	Proposed a dynamic imprecise-aware network selection algorithm	**Network Attributes:** bandwidth, RSS, SNR, delay, jitter, loss **Services:** video, file upload **User Preference:** no	1. The extreme values of network attribute values 2. The mean and standard deviation of network attribute values	**Advantages:** The network selection in the state of imprecise value can be better handled **Disadvantages:** User preference is not considered
[29]	TOPSIS+ Utility function	Improved policy for network selection combining the enhanced-	**Network Attributes:** cost, security, bandwidth, delay, jitter, loss; **Services:**	1. Average of reversal phenomenon 2. Average of ping-pong effect 3. Average of handoffs	**Advantages:** Have better performances concerning three evaluation parameters: the reversal phenomenon, the ping-pong

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		TOPSIS method and the utility function.	background, conversational, interactive, and streaming **User Preference:** no	failures	effect and the handoff failures. **Disadvantages:** User preference is not considered
[88]	Utility function + Fuzzy Logic	Proposed a network selection algorithm combining cost function and QoS calculation	**Network Attributes:** RSS, rate, SNR, throughput, error **Services:** telephony services, online radio, video conferencing, and video streaming **User Preference:** Different fuzzy inference rules are established for different candidate networks	1. Number of network selection 2. Utility degree 3. Number of contented users with desired QoS	**Advantages:** Considering quality of service and user satisfaction **Disadvantages:** The impact of the criterion value on various services is not considered
Proposed mechanism	Utility function+ Entropy+ Triangular FAHP + fuzzy logic+ TOPSIS	Design a multi-criteria access selection mechanism combining a variety of methods and supporting service characteristics user preferences	**Network Attributes:** bandwidth, delay, jitter, packet loss ratio and price **Services:** background, conversational, interactive, and streaming **User Preference:** Subjective weight, network attribute preference, candidate network preference value	1. Average values of network attributes 2. Selected times of each candidate network 3. Average user gain 4. Number of handovers between networks 4. Number of unnecessary handovers between networks	**Advantages:** Various mathematical models are integrated, and network attributes, business characteristics and user preferences are considered at the same time **Disadvantages:** The user's status information is not considered

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2.6 Summary

In HWN, where overlapping coverage of wireless signals exists, different QoS requirements of terminal services, different performance of wireless networks and different preferences of users, it is an important problem to design an access selection algorithm that can guarantee the most suitable network access for users in the further development of HWN. In view of this problem, a large number of researchers have made unremitting explorations and achieved a lot of results. This chapter mainly classifies and summarizes the results of access selection algorithms for HWN, analyses the ideas and advantages and disadvantages of each access selection algorithm in detail. In addition, this chapter also summarizes the main problems existing in this kind of algorithm at present, and puts forward the future research directions.

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CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Introduction

The overall objective of this research is to design a new multi-criteria access selection mechanism suitable for HWN environment, which can consider service characteristics and user preferences at the same time, ensure QoS, and improve user experience. To achieve these objectives, this research requires a credible research framework to promote the systematic achievement of goals through correct verification, validation technique and evaluation of the proposed mechanisms.

This chapter gives a thorough explanation of the research methodology that was employed in this research. This research has followed the Design Research Methodology (DRM) [129] approach, which helps to fulfill the objectives with the explicit phase by phase description. DRM is a clear guide for obtaining a research framework that is acceptable in academia and industry, hence it was used in this research.

The structure of this chapter is as follows: Section 3.1 Introduction provides the content and structure of this chapter. Section 3.2 Research Approach includes a comprehensive overview of all the issues in this research by using DRM. Section 3.3 Research Clarification (RC) clarifies the step of research clarification, which establishes the methods used to produce the research plan in this stage. Section 3.4 Descriptive Research (DS-I) provides a thorough comprehension of the current scenario and helps to understand conceptual model, the overall research project's blueprint. Section 3.5 Prescriptive Study (PS) focuses on the design of decision making strategy in network access selection. Furthermore, section 3.6 Descriptive Study-II (DS-II) discusses the performance evaluation process, including simulation environment parameter setting, scenario and performance metrics. Lastly, this chapter is summarized in section 3.7.

3.2 Research Approach

Design Research Methodology (DRM) is a systematic, integrated, iterative research method that combines theory with engineering technology practice. It not only has the precision and systematicity of traditional research methods, but also helps researchers to grasp the studied problem more quickly and comprehensively in the process of solving practical problems [130]. Additionally, it aids in making design research more rigorous, effective, and efficient in terms of academic and practical outcomes. DRM has been used for this research because of the framework's iterative property.

According to

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Figure *3.1*, the DRM approach consists of four key stages: Research Clarification (RC), Descriptive Study-I (DS-I), Prescriptive Study-I (PS-I), and Descriptive Study-II (DS-II). Three steps are depicted horizontally in the process in

Figure *3.1*: methods, DRM stages, and outcomes. Method indicates the process used, DRM stages indicate the objective, and outcomes indicate the outcomes of the process at each stage. As shown in

Figure *3.1*, thick arrows indicate the input and output for each stage, whereas thin arrows indicate the direction of flow iteratively through each stage.

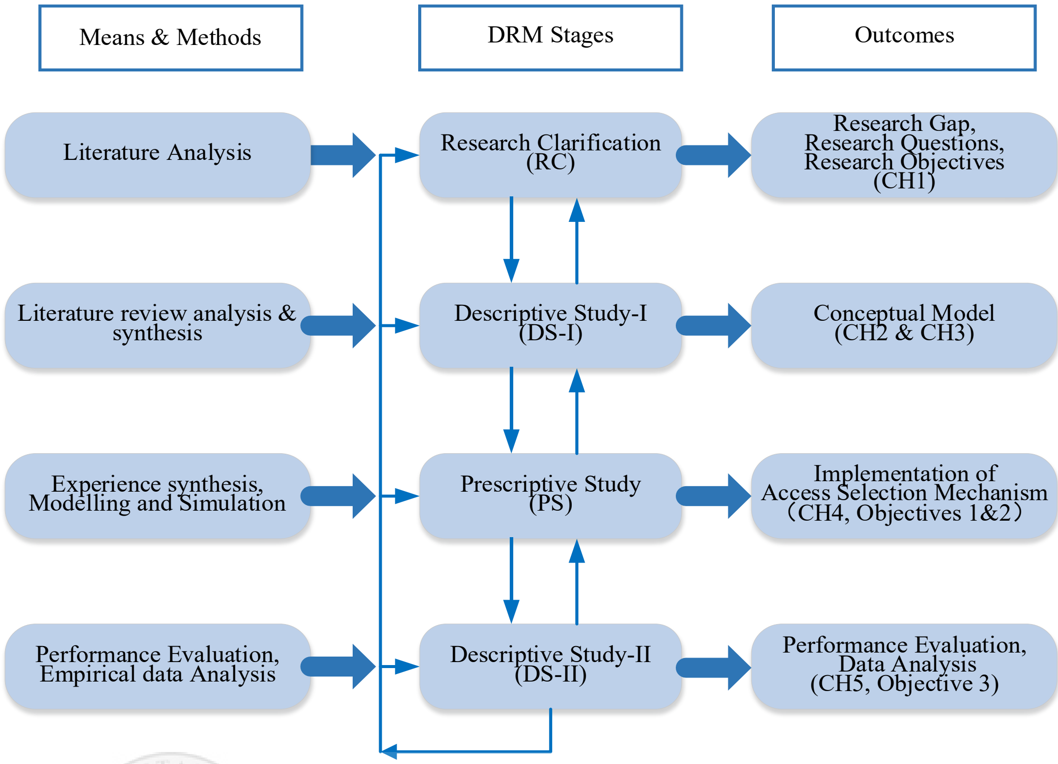

Figure 3.1. Research Approach

3.3 Research Clarification (RC)

RC is the first stage of DRM. The RC phase of the research project focuses on comprehending the research area accurately. This phase includes five iteration steps to arrive at the incipient research plan described in Figure 3.2. In this stage, the main research field of HWN environment is reviewed, focusing on the choice of network access. On the basis of literature research, this research summarizes the research methods, scope, pertinent mechanisms and anticipated contributions [131].

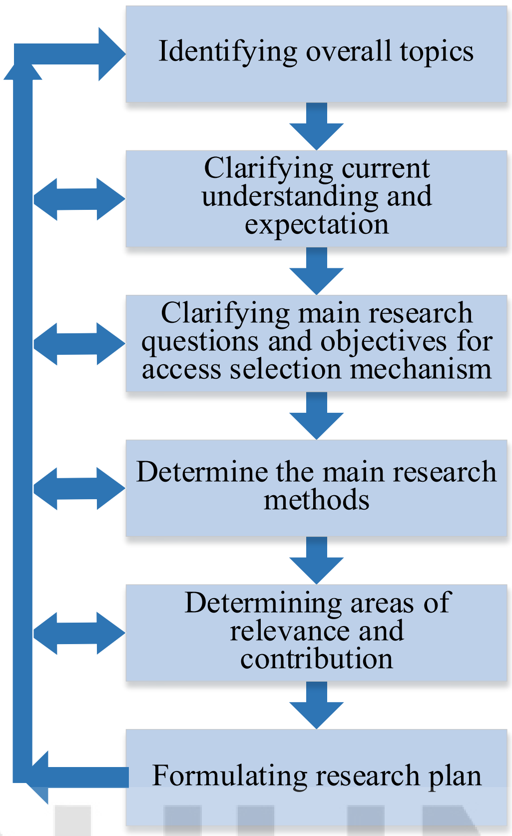

Figure 3.2. Main Steps in Research Clarification

Generally speaking, the outcomes of the RC stage are in Chapter One. The outcomes are the entire research plan, which specifically contains the following details:

i. Key research points and motivation;

ii. Research problems, research questions and research objectives;

iii. Research scope, research steps and research significance.

3.4 Descriptive Study (DS-I)

3.4.1 Main Steps in Descriptive Study-1

After the RC stage, the overall research plan is completed and the research enters the 2nd stage, known as DS-I. This stage aims to introduce the research in a comprehensive manner. DS-I was used to fully comprehend the current circumstances. It entails a critical analysis of literature and empirical research in the research field. In order to acquire a full grasp of the present issues and directions, several empirical research were critically reviewed throughout this research and a thorough analysis of the current recommendations was conducted. As indicated in Figure 3.3, DS-I contains four steps and multiple iterations. Each step seeks to advance understanding and may result in additional empirical research or literature review, which would then allow for the redefinition and revision of performance and conceptual models.

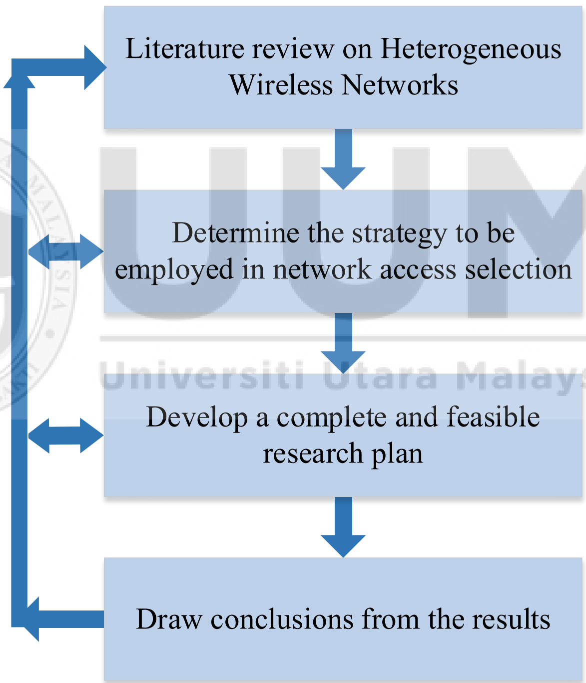

Figure 3.3. Main Steps in DS-I

Figure 3.3 describes the main steps of this stage. This stage starts with a literature review. The literature review collects the reliable literature from the most trusted search engines and databases, such as Google Scholar, Web of Science, SpringerLink, Scopus, IEEE Xplore, ACM, and Science Direct. The last step is to determine the parameters of bandwidth, packet loss ratio, delay jitter, price and delay by selecting network attributes. Because different network attributes have different importance for different user services in the process of network access selection, we determine the corresponding weights according to the preference degree of user services for a network attribute. In this research, we divide the methods of determining weights into objective weighting method and subjective weighting method, integrate the objective weights and subjective weights of network attributes, get the comprehensive weights of network attributes, and finally draw the general conclusion of this research.

The outcomes of DS-I include:

i. A conceptual model of access selection mechanism in HWN considering both service characteristics and user preferences,

ii. Critical analysis of the related research to improve the research plan proposed in the stage of Research Clarification.

3.4.2 Conceptual Model of Access Selection Mechanism

Previous research on HWN access selection has mainly focused on the comprehensive performance of wireless networks, while ignoring service characteristics and user preferences [50], which easily leads to a disconnect between the access selection mechanism and actual requirements, thus failing to improve QoS and user experience. Therefore, in the design of the access selection scheme, this research not only considers the impact of network performance on user services, but also considers the user preferences. This research designs a new access selection mechanism to improve user experience. The proposed mechanism uses utility functions to calculate the utility value of each network attribute, uses entropy method to calculate the objective weight of network attributes, uses FAHP to calculate the subjective weight of network attributes, uses fuzzy logic theory to calculate the score of network attributes, uses FAHP to calculate user preference values, and finally, uses TOPSIS method to calculate the comprehensive score of candidate networks. The conceptual model of the method is shown in Figure 3.4.The left part of the proposed mechanism is designed to achieve the first objective: designing an access selection scheme to support the diversity of service characteristics. The right part is designed to achieve the second objective: designing an access selection scheme to support the differences of user preferences.

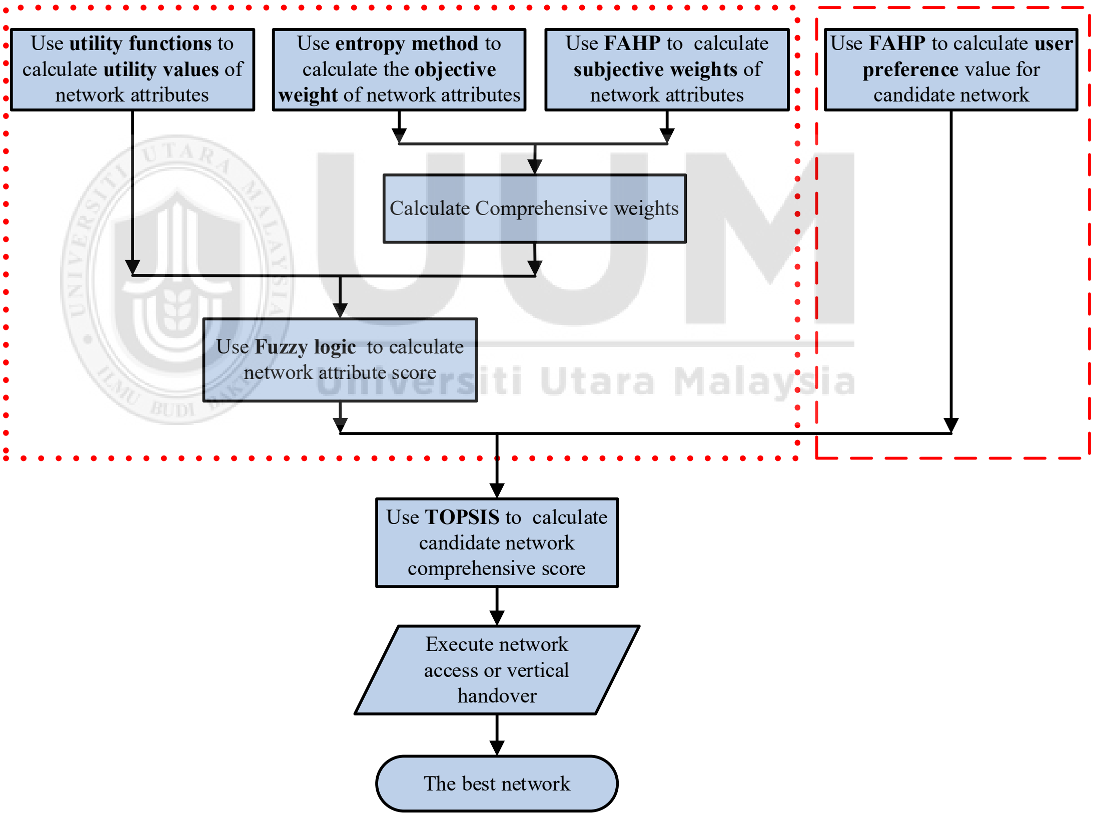

Figure 3.4. Conceptual Model of Access selection mechanism

Next, we analyze the definition of network attribute parameters and measurement methods. In this research, we select the network attribute parameters as bandwidth, delay, delay jitter, packet loss ratio, price. According to the different service characteristics and QoS requirements, the utility value calculation method of network attributes for different services is studied, as shown in Figure 3.5.

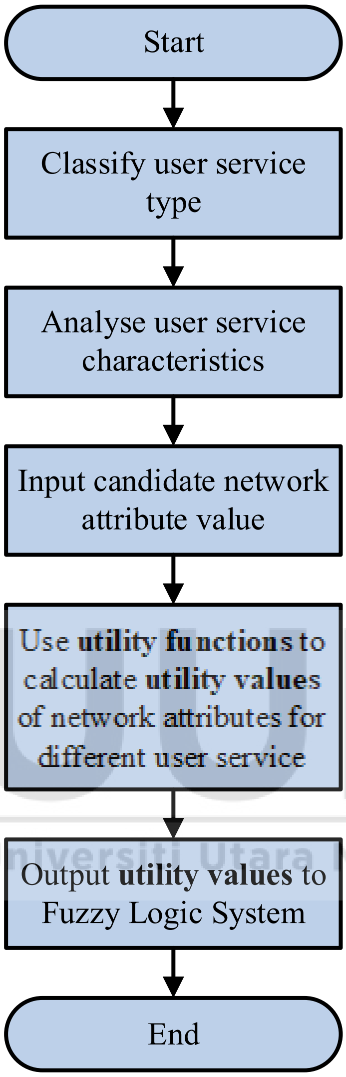

Figure 3.5. Flow Chart for Calculating the Utility Values of Network Attributes

Because different network attributes have different importance for different user services in the process of network access selection, we determine the corresponding weights according to the preference degree of user services for a network attribute. In this research, we divide the methods of determining weights into objective weighting method and subjective weighting method. We use entropy method to calculate the objective weight of network attributes, as shown in Figure 3.6. We use FAHP to calculate subjective weights of network attributes, as shown in Figure 3.7. We integrate the objective weights and subjective weights to calculate the comprehensive weight of network attributes.

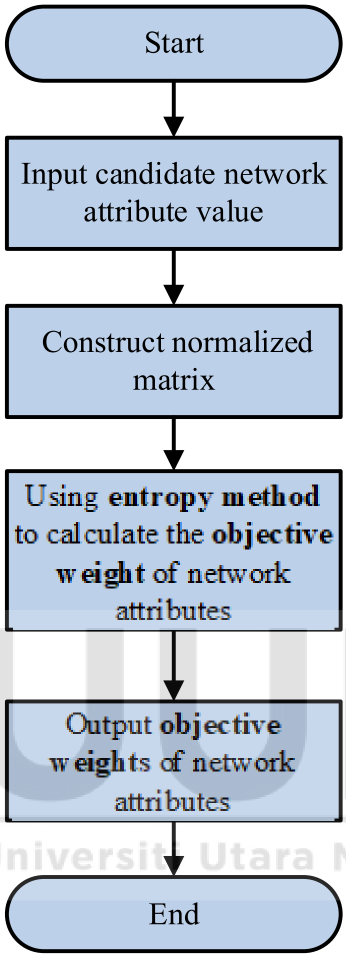

Figure 3.6. Flow Chart for Calculating Objective Weights of Network Attributes

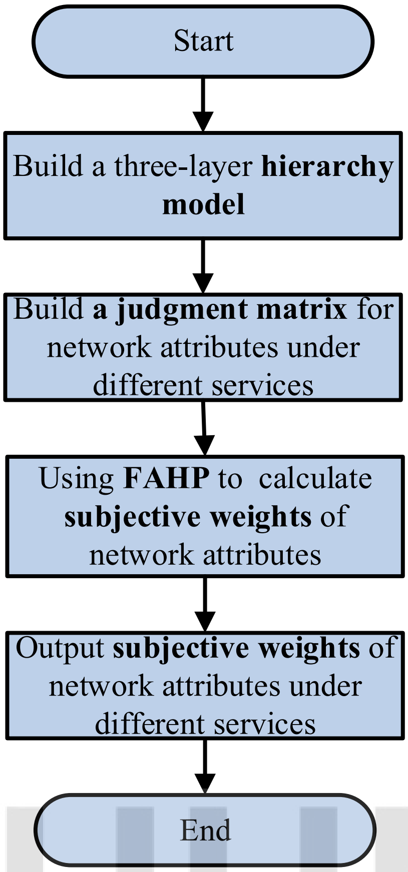

Figure 3.7. Flow Chart for Calculating Subjective Weights of Network Attributes

According to the utility value and comprehensive weight, fuzzy logic is used to further calculate the network attribute score based on service characteristics, as shown in Figure 3.8.

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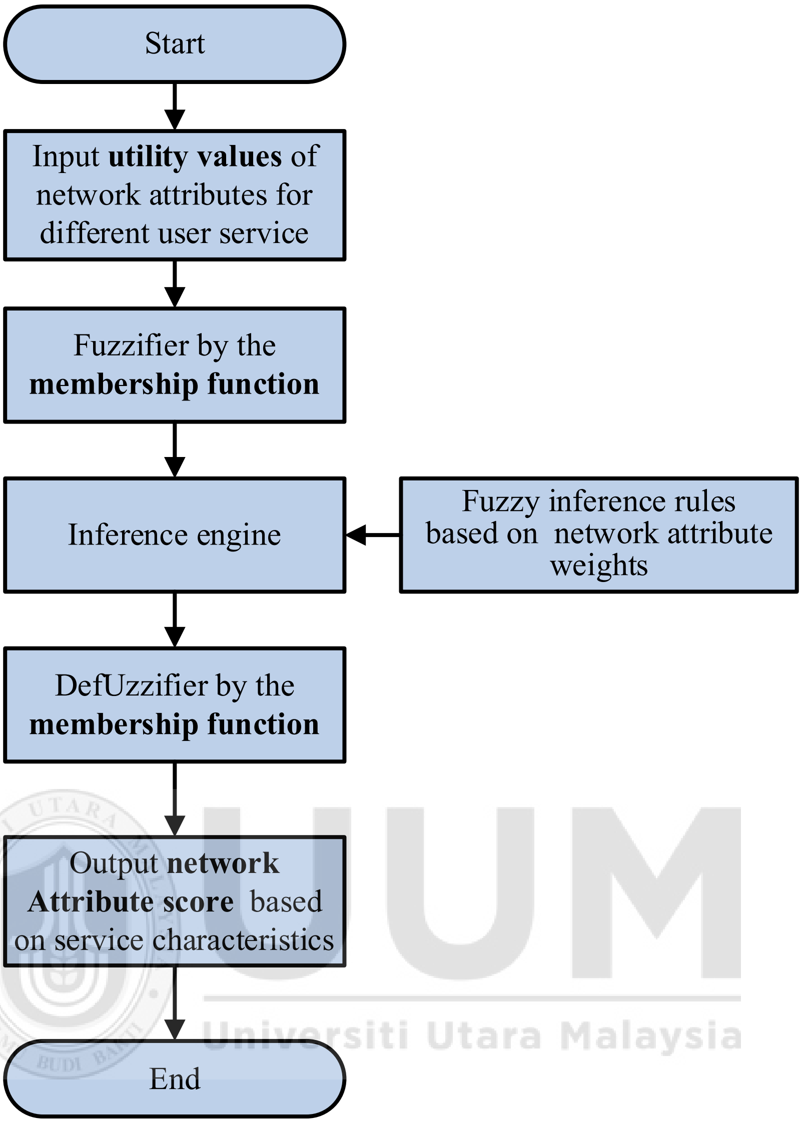

Figure 3.8. Flow Chart for Calculating the Network Attribute Score

According to the user's preference value for network attributes, the preference value for potential networks is further calculated using FAHP, as shown in Figure 3.9.

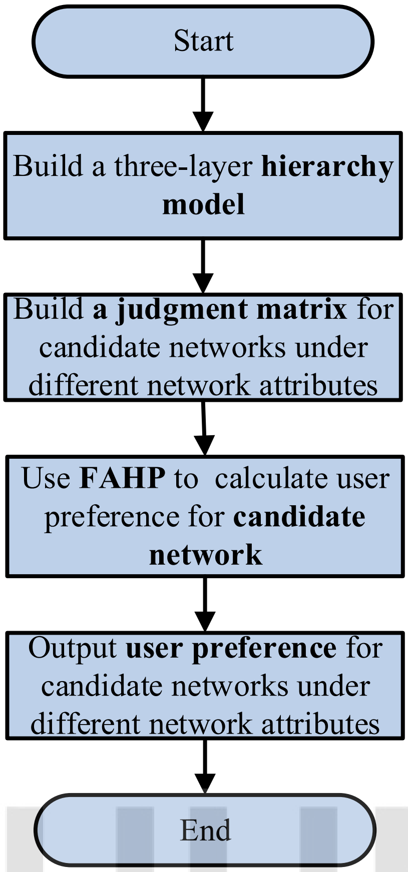

Figure 3.9 Flow Chart for Calculating User Preference Values of Candidate Networks

Finally, in accordance with the network attribute score and user preference value for candidate networks, the comprehensive scores of candidate networks are calculated using TOPSIS, as shown in Figure 3.10. Additionally, due to user mobility and changes in wireless channel performance, the network attribute values that users receive change. Therefore, the scores of candidate networks need to be recalculated and sorted, which might lead users to switch between candidate networks. This research reduces the ping-pong effect using the user preference for different candidate networks, thereby avoiding frequent switching between different networks due to small changes in network performance.

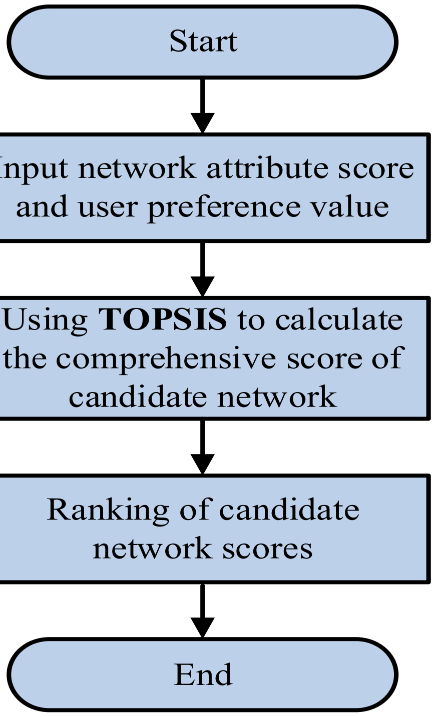

Figure 3.10. Flow Chart for Calculating the Comprehensive Scores of Candidate Networks

3.5 Prescriptive Study (PS)

3.5.1 Main Steps in the Prescriptive Study Stage

PS is the main stage of DRM because it involves the design of the suggested research mechanism. The modeling and simulation process of the suggested research mechanism is shown in Figure 3.11. Based on the research processes from conceptual model to system model verification and validation, the main steps of PS are described. Figure 3.11 describes the main steps of the access selection mechanism. Following the same steps as in Figure 3.11, firstly, the strategic implementation completes the conceptual model design of the proposed mechanism, and then the conceptual model is transformed into the analytical model using mathematical equation formulas. Next, the formulated equations are converted into programmable code for MATLAB tools, which can be used to run experiments many times. Finally, the designed and implemented mechanism is accredited after verification and validation.

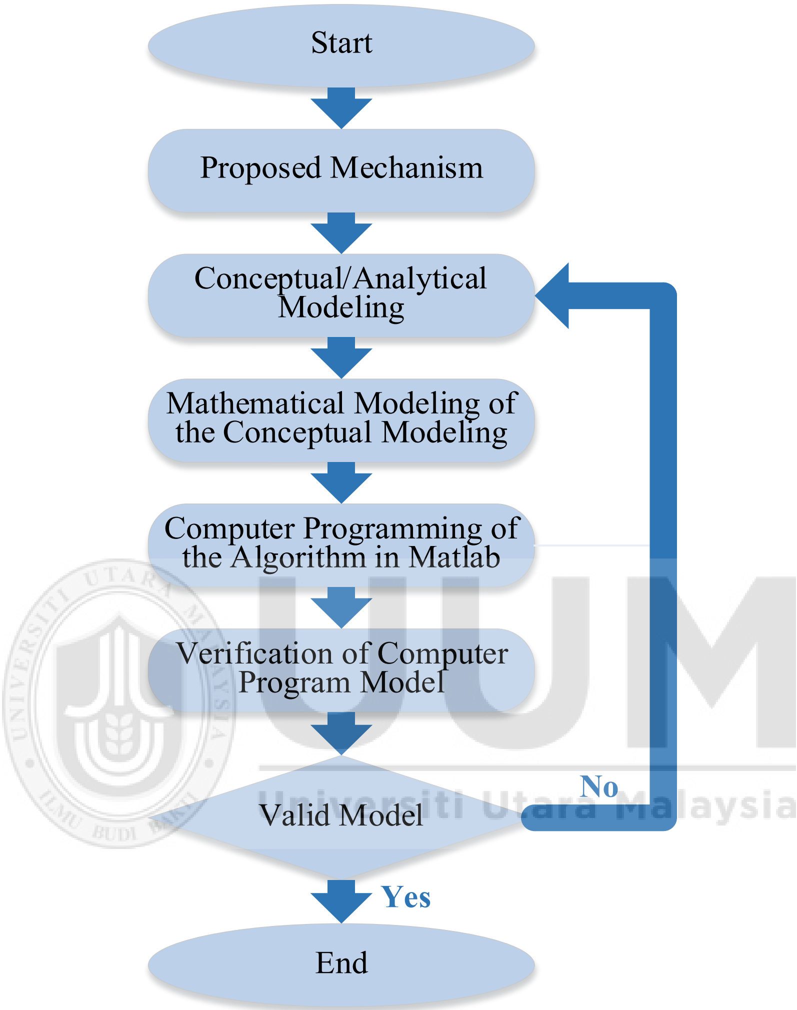

Figure 3.11. Main Steps in the Prescriptive Study Stage

The planned outcomes of the Prescriptive Study stage include:

i. Achieve objectives one and two.

ii. Design and implement the proposed mechanism.

iii. Verify and validate the proposed mechanism.

3.5.2 Verification and Validation

Model verification, as shown in Figure 3.12, is the process of confirming if the mechanism has been correctly converted from one form to another with sufficient precision [132]. In this research, the verification step is achieved by converting the flowchart or pseudocode into executing program in a computer. The mechanism should be encoded and verified correctly, that is, without any errors or bugs. Lastly, all mechanisms should be encoded into executable programs in the MATLAB language by the end of the verification step. And the MATLAB code can be executed correctly and obtain the correct results [133].

The step of verification is used to ensure that:

i. The mechanism can be programmed properly.

ii. All steps have been appropriately followed.

iii. There are no syntax errors, semantic errors, or bugs in the model transformation from conceptual model to the program design.

iv. More cases are tested to achieve a high level of statistical confidence.

When the initial data is programmed into MATLAB code, verification ensures that there are no syntax errors. If the compiled result is successful, it indicates that the verification process has been completed correctly. The absence of semantic errors guarantees the accuracy of the expected results obtained from the process of converting raw data into MATLAB code. Finally, the experimental results will be obtained by executing MATLAB code.

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The experimental results are validated through comparison and evaluation with current representative relevant mechanisms. The evaluating findings implicitly confirm the proposed mechanism in addition to evaluating the performance advancement.

Validation is substantiation that is a computerized model within its domain of applicability possesses a satisfactory range of accuracy. Validation is done to ensure that all mechanisms satisfy their expected demands in terms of the strategies used and the outcomes attained. Furthermore, the conceptual model's validity ascertains: firstly, the conceptual model's presumptions are valid; Secondly, the model represents the entity of the problem, and its structure, logic, mathematics, and causal relationships are ‘reasonable’ for the expected results of the model.

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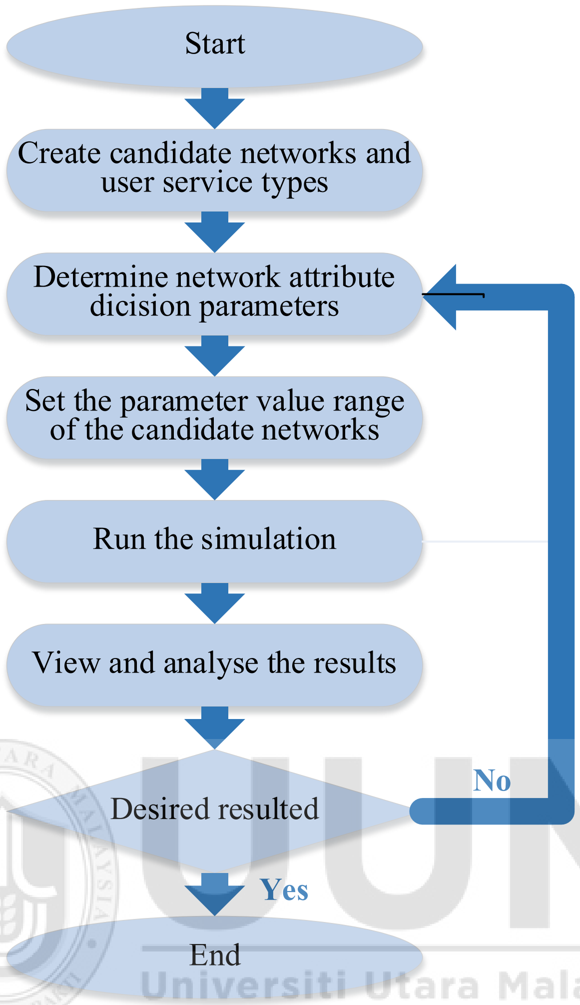

Figure 3.12. Main Steps in the Verification and Validation Stage

Table 3.1 briefly describes the multiple approaches to validate and endorse the designed conceptual model. The two validation approaches used in this research are: (1) Evaluation of other Models and (2) Constraint Changeability-Sensitivity Analysis, which are items 1 and 4 in Table 3.1. The analytical model supporting user preferences is designed by combining the differences in service characteristics and user preferences. Then, the analytical model is converted into the analytical formulation of equations. Finally, the equation formulation is converted into MATLAB code.

The first step of validation is implicitly completed by selecting a theory with a consistency range appropriate for the implementation of the mechanism. For the purpose of validating the proposed mechanism, the final outcomes of the proposed mechanism are compared to the current representative related mechanisms. The experimental results gained in many cases were carefully examined to see whether the proposed mechanism is valid. ln Chapter Five, which covers performance analysis, a thorough numerical analysis for the verification and validation of outcomes is offered. The simulation experiment is randomly performed for a large number of decision data to test the validity of the proposed mechanism.

Table 3.1
Model Validation Approaches

Sl.no	Validation Method	Description
1	Evaluation of other Models	The correctness of the simulation results is validated by comparing with current representative related models.
2	Appearance Validity	Obtaining the expert's evaluation on the model's accuracy.
3	Previous Data Validation	Use the historical data to create and evaluate the model.
4	Constraint Changeability-Sensitivity Analysis	This method includes altering the model's input parameters in order to assess the influence of the actual system on the output behavior of the model. Before injecting the model, sensitive parameters should be made accurate enough.
5	Predictive Validation	The system's behavior is predicted by the model, which is then used to compare the system's behavior to its forecast to see if they match. The system's data may originate from the operating system or may be acquired through system trials, including field testing.

3.6 Descriptive Research-II (DS-II)

The DS-II emphasizes evaluating the proposed mechanisms and the intended results. This phase of the research is significant since it details the quantification of this research's contribution by precisely meeting the design requirements. The traditional

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approaches for evaluating performance include analytical modeling, simulation, and verification.

3.6.1 Evaluation Approach Consideration

Evaluation techniques are essential for measuring the system's performance. It is crucial to choose the appropriate evaluation method and tool [134]. The advantages and disadvantages of performance evaluation methodologies are listed in Table 3.2. The two main categories of the method are performance modeling and performance measurement.

Table 3.2
Comparison of Performance Evaluation Techniques

Criteria	Performance Modeling		Performance Measurement
	Analytical Modeling	**Simulation**	
Time Required	Low	Medium	High
Accuracy	Low	Medium	High
Tool	Formal Method	Computer Programming	Instrumentation
Trade-off evaluation	Easy	Medium	Difficult
Cost	Small	Medium	High

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The actual system uses real-time parameters for performance measurement. The measurement can be carried out via test tables, software monitoring, off-chip hardware monitoring, on-chip performance monitoring, and other methods. This assessment has high accuracy, but it needs to build the actual environment. The cost and time are high, and it is difficult to do trade-off evaluation. Performance modeling conducts performance evaluation by simulating actual systems. This performance modeling technology can achieve medium accuracy, and the time, cost and trade-off evaluation are all medium. Analysis modeling is a mathematical expression based on the theoretical or mechanism of operational law, queuing network, process algebra, and random network. The time, cost and trade-off evaluation are all low, but the accuracy of the evaluation is also low [135].

Performance modeling techniques include analytical modeling and simulation. Analysis modeling uses mathematical concepts and language to describe the system, including logical models based on a certain theoretical, and its experimental results can be reproduced. Analysis modeling refers to a set of equations that use mathematical symbols to represent the actual system. The equations can be converted to executable code through computer programming, and the intuitive graphics can be further generated by running the code. To obtain the required results, users can freely change the input parameters of the program. In addition, the analysis modeling is actually converted through simulation for performance evaluation. In order to verify the proposed mechanism, the analysis modeling is converted into MATLAB code for data analysis and comparison.

After in-depth analysis of different performance evaluation techniques, this research selected performance modeling technology to achieve the research objectives described in Chapter 1. Performance modeling is a standardized technique that considers all the time, cost, difficulty, and accuracy required for performance evaluation, and it is widely adopted by researchers [136].

3.6.2 Evaluation Environment

i. Performance evaluation software

MATLAB is a platform that offers an interactive interface for programming, visualizing data, and doing calculations. MATLAB applications are created using MATLAB tools. Most MATLAB usage involves running text files with MATLAB code or inputting code, including functions and scripts, directly into the command window. As part of the planned research, MATLAB will be used to implement the suggested access selection method.

ii. Experiment Steps

All simulation experiments discussed in Chapter 5 Performance Analysis will be implemented using the MATLAB platform. Firstly, the analytical model is converted into mathematical equations, and then the mathematical equations are converted into executable MATLAB code which is used for multiple iterations and matrix analysis in MATLAB. Finally, relevant data graphs are obtained by executing MATLAB code.

In the experimental environment, we will deploy four candidate networks with overlapping signal ranges of different types. Mobile users move in a random direction within the signal range, assuming they are a multi-mode mobile terminal (MMT), and can choose to connect to any wireless network.

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In the experiment, the user first detects and collects data for each network attribute within the HWN signal range. The user then sorts and chooses potential networks based on the information and the network access technique. Finally, the network selection is completed according to the access selection mechanism. In this research, five network attribute data collected by users are available delay, bandwidth, packet loss ratio, delay jitter, and price.

The experiment of this research includes two steps. The first step involves conducting experiments using static default data for network attributes. It mainly evaluates the ranking of candidate network scores obtained by various algorithms. The second step is to conduct experiments under the dynamic changes in the performance of candidate networks. In this step of the experiment, the network attribute value changes dynamically between the preset minimum value and the maximum value when it changes dynamically. It primarily evaluates the number of selected candidate networks and the number of handovers calculated by various schemes.

iii. Performance Metrics

The selection of relevant metrics to measure the performance of the proposed algorithm is one of the crucial aspects in performance evaluation. Performance metrics make it easier to measure performance. Wang et al. [137] provided several relevant performance metrics for access selection, as follows:

a. Average values of network attributes of the most suitable network

   The formula for calculating the average value of each network attribute parameter is shown in formula 3.1-3.5 below. These metrics are mainly used to calculate the average value of network attribute parameters of the most suitable network selected by different services in the dynamic network environment. These metrics are used to evaluate whether the selected network meets service characteristics and QoS requirements.

$$AverageBandwidth = \frac{\sum_{i=1}^{n} Bandwidth_{best\_network}}{n} \tag{3.1}$$

$$AverageDelay = \frac{\sum_{i=1}^{n} Delay_{best\_network}}{n} \tag{3.2}$$

$$AverageJitter = \frac{\sum_{i=1}^{n} Jitter_{best\_network}}{n} \tag{3.3}$$

$$AverageLoss = \frac{\sum_{i=1}^{n} Loss_{best\_network}}{n} \tag{3.4}$$

$$AveragePrice = \frac{\sum_{i=1}^{n} Price_{best\_network}}{n} \tag{3.5}$$

Where,

$Bandwidth_{best\_network}$, $Delay_{best\_network}$, $Jitter_{best\_network}$, $Loss_{best\_network}$ and $Price_{best\_network}$: are average bandwidth, average delay, and average jitter, average packet loss ratio, average price, respectively.

n is total number of network selections.

b. Number of candidate networks selected: This metric is used to calculate the probability of each candidate network being selected for different services. This metric is used to evaluate the relationship between service characteristics and user preferences and candidate networks.

$$NoS = \sum_{i=1}^{n} candidate\_network_{\text{selected}} \tag{3.6}$$

Where,

$candidate\_network_{\text{selected}}$: When the candidate network is selected, the number of times increases by 1.

c. Number of vertical handovers and number of unnecessary vertical handovers: If the user leaves the currently connected network and connects to another network, the number of handovers will increase by 1. If the user leaves the currently connected network, connects to another network, and then reconnects to the current network, the number of unnecessary handovers will increase by 1. The number of vertical handovers and the number of unnecessary handovers are two indicators mainly used to evaluate and compare the ping pong effect of the proposed mechanism with other mechanisms.

d. User gains: This metric is mainly used to evaluate and compare the quantified benefit from each access selection mechanism. The quantified benefit is defined by the following formula 3.7 [52]:

$$Gains_{ij}^{s} = \lambda_{ij}^{s} \prod_{k=1}^{n} r_{jk}^{w_k^s}, \qquad 1 \le i, j \le m, 1 \le s \le t \tag{3.7}$$

Where,

s is the type of user services;

$Gains_{ij}^{s}$ stands for the gains of the vertical handover from present network i to the new network j, for the user services$s$;

n is the number of network attributes;

λ_{ij}^{s} stands for the equivalent detrimental affect element on the handover;

r_{jk} represents the element of R, R is the decision matrix of network parameters;

w_k^s stands for the attribute k's weight for the user services s;

λ_{ij}^{s} is given by formula (3.8).

$$\lambda_{ij}^{s} = \begin{cases} 1 & , i = j \\ constant & , i \neq j \end{cases} \tag{3.8}$$

3.7 Summary

In order to ensure that the research objectives can be met, this chapter has provided a detailed description of the research methodology. This research focuses on designing an access selection mechanism supporting user preferences in HWN. This strategy considers both network performance and user preferences. According to DRM, the research was broken down into four key actions in this chapter. The first stage, named Research Clarification, discusses how to assist the early phase of this study. The purpose of RC is to refine and identify research problems, research questions and research objectives that are realistic and academically worthwhile. The second stage, named Descriptive Study-I, outlines steps to understand the current situation, design reference models, and propose a conceptual model. The third stage describes the methods used to design the proposed access selection mechanism, called Perspective Research. The final stage, DS-II, discusses the evaluation of design mechanisms.

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CHAPTER FOUR

THE IMPLEMENTATION OF MCASM

In Chapter Two, we analyze the related algorithms of HWN access selection in detail, and in Chapter Three, we establish the research method of this thesis. The process of access selection includes three stages: decision information collection, decision making and decision execution. This chapter focuses on the second stage (i.e., decision making). Aiming at the problems of existing algorithms, this thesis integrates a variety of mathematical models and proposes a multi-criteria access selection mechanism (MCASM) based on user preference.

This chapter is organized as follows. Section 4.1 introduces the network environment and algorithm module. Section 4.2 introduces the calculation of the utility value of the network attribute. Next, Section 4.3 introduces the calculation of network attribute weight. In addition, Section 4.4 introduces the calculation of the score of the network attribute. Section 4.5 describes the calculation of user preference values. Finally, Section 4.6 introduces the calculation of the comprehensive score of the candidate network. Section 4.7 summarizes Chapter 4.

4.1 System Model

4.1.1 Network Environment

With the use of four wireless networks (UMTS, LTE, WLAN, and WiMAX), a HWN will be created in this thesis that has overlapping signal ranges. Mobile users are supposed to move randomly and to be able to get signals via every wireless network and network attribute value (such as bandwidth, jitter, delay, packet loss ratio, price). Furthermore, it is supposed that any of the four wireless networks listed above may be selected by the user terminal device, which also has a multi-mode interface. Finally, the thesis categorizes the user services into four groups in accordance with 3GPP specifications (i.e., conversational, streaming, interactive, and background categories). Figure 4.1 depicts the access selection scenario for HWN used in this thesis.

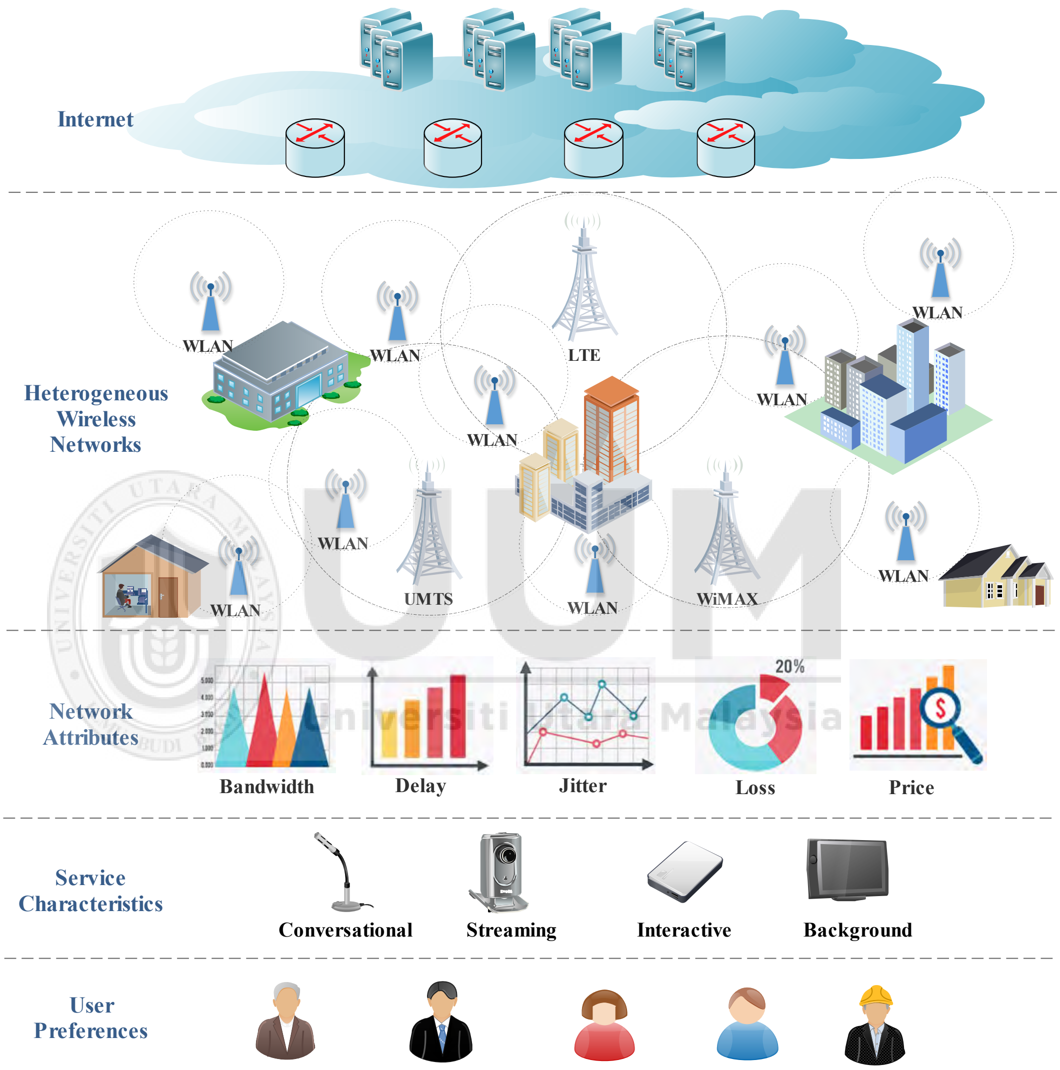

Figure 4.1. Access Selection Scenario for HWN

4.1.2 Algorithm Module

The access selection algorithm designed in this thesis primarily consists of five functional calculation modules, namely the utility value of network attribute, the weight of network attribute, the user preference value, the score of network attribute, and the comprehensive score of candidate network, respectively. The access selection algorithm framework is shown as Figure 4.2. The main functions of each module are described below.

i. Since the measurement ranges of network attributes are different (e.g., the bandwidth usually ranges from 0 Mbps to 100 Mbps, and the delay usually ranges from 20 ms to 200 ms), the main function of the module for network attribute utility value calculation is to convert the actual values of attributes in different measurement ranges into normalized values between [0-1] according to different service characteristics.

ii. The main function of the network attribute weight calculation module is to calculate the weight of each network attribute in different service types. The greater the weight, the more important the network attribute is to the service, and vice versa. The value range of the weight is [0-1], and the sum of weights of the five network attributes is 1.

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iii. The main function of the module for network attribute score calculation is to calculate the network attribute score of each candidate network according to the utility value and weight of each network attribute.

iv. Since different users have different preferences for different networks, the main function of the module for calculating user preference value is to calculate the user preference value for each candidate network. The value range is [0-1]. The higher the value, the more preferred the user is to the network, and vice versa.

v. The primary task of the module for candidate network comprehensive score calculation is to synthesize the comprehensive scores of the candidate networks in accordance with the scores of network attribute and user preference values.

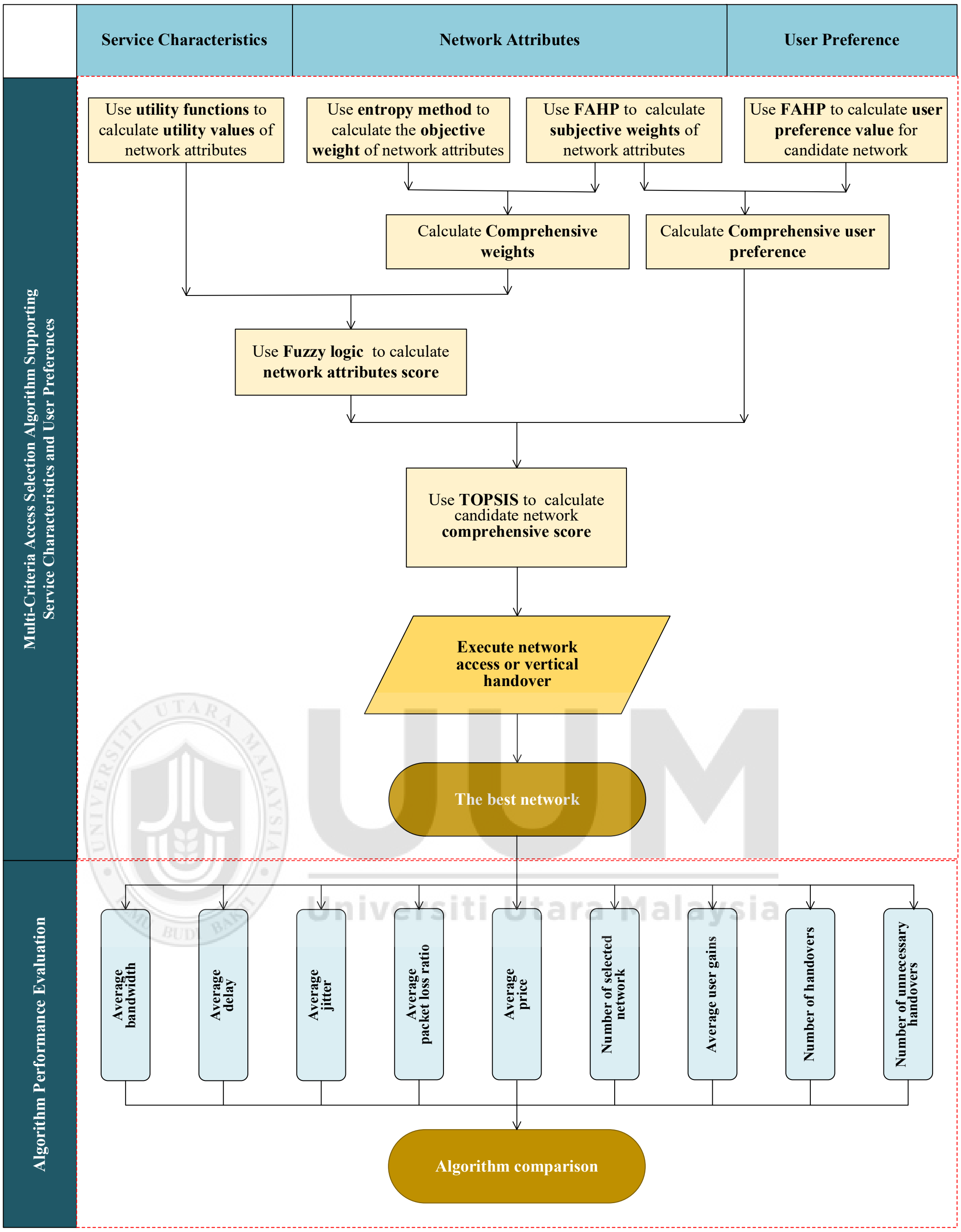

Figure 4.2. Access Selection Algorithm Framework

4.2 Calculation of Utility Values of Network Attributes

4.2.1 Service Characteristic Analysis

In the HWN environment, different users will run different services, and each service type has different requirements for network performance, and the access selection algorithm should access users to the most appropriate network according to different services requirements. In this thesis, according to the 3GPP standard, we divide the service types of users into four types: conversational services, interactive services, streaming services, and background services [59, 138], the characteristics of each service are analyzed in detail below and show in Table 4.1:

i. Conversational Services

Conversational services mainly include voice communication and video communication. This service has stringent requirements for delay and jitter because users expect a seamless call and on-time delivery of the information they transmit. Predominantly, the total data of this type of service is not exceptionally large after being compressed by data compression algorithms, so the bandwidth and cost demands for conversational services are not high.

ii. Interactive Services

Interactive services are usually web browsing and database retrieval. This kind of service expects that the operation can get a fast response and the response time for each operation should be consistent. Additionally, these services usually require a certain amount of bandwidth, but when the bandwidth meets the requirements, higher bandwidth does not significantly enhance the quality of service.

iii. Streaming Services

Streaming services primarily offer on-demand audio and video online. Considering that a piece of music or video frequently contains large amounts of data, streaming services have higher sensitivity to bandwidth and price. In addition, due to the application of buffering technology, streaming services have lower

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requirements for jitter. Streaming services have higher requirements for delay compared with background services.

iv. Background Services

The majority of background services consist of data downloads and other actions. This type of service does not run in the foreground, but rather in the background, performing some relatively time-consuming and large-volume data transmission operations. There is no direct interaction with the user, who is typically unaware of delays or jitter. Notwithstanding, in order to complete the transmission of a large amount of data as soon as possible, this type of service requires a large bandwidth. Be that as it may, because of the large amount of data and long transmission time, the price is required to be as low as possible. In addition, background services are characterized by no strict requirements for delay, packet loss, and jitter.

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Table 4.1
Service Types and Characteristics

Service Categories	**Service Characteristics**	**Typical Service**
Conversational	Meet the bandwidth threshold, High requirements for delay and jitter, General requirements for loss, Lower requirements for price.	VoIP and video conferencing, etc.
Interactive	A certain bandwidth is required, High requirements for jitter, delay and loss, Low requirements for price.	web browsing, database retrieval, etc.
Streaming	High requirements for bandwidth and price, General requirements for loss and delay, Low requirements for jitter.	real-time video/audio, etc.
Background	High requirements for price and bandwidth, Low requirements for delay, loss and jitter	file download, delivery of e-mail, etc.

4.2.2 Calculation of Network Attribute Utility Value

Wang et al. [63] provided a detailed explanation of the utility function network selection principle, as well as the definitions of various utility functions and their curve forms. The purpose, benefits, and drawbacks of employing utility theory to develop the network selection algorithm are summarized [62]. Salih et al. [139] pointed out that due to different services have varied requirements and satisfaction with network attributes, multiple utility functions are created for services with varying degrees of flexibility.

In Chapter 2, we analyze the utility function-based network selection algorithm. In this chapter, the utility theory is used to measure users' satisfaction with network attribute values, and various utility functions (e.g., linear function, sigmoid function, exponential function) are used to convert users' satisfaction into utility values for quantification in the algorithm design of the network selection. The definitions of utility function are shown in Table 2.4. x in the table is the actual value of the network attribute, and a, b, c, d are the adjustment coefficients of each utility function curve. For benefit attributes (e.g., bandwidth), users are more satisfied when the actual value is higher, and the utility value can be expressed as $u(x)$. For cost-based attributes (e.g., delay, jitter, loss, and price), the user's satisfaction increases with decreasing actual value, and the utility value can be expressed as $1 - u(x)$. Generally speaking, the utility value of the highest user satisfaction is 1, while the utility value of the least user satisfaction is 0, so the utility value range is from 0 to 1.

Due to different service characteristics, the same network attribute value will have different levels of satisfaction for different users (e.g., the satisfaction for users of the conversational service may be high for a bandwidth of 2 Mbps, but the satisfaction for users of the streaming service may be low for the same bandwidth of 2 Mbps, as shown in Figure 4.3).

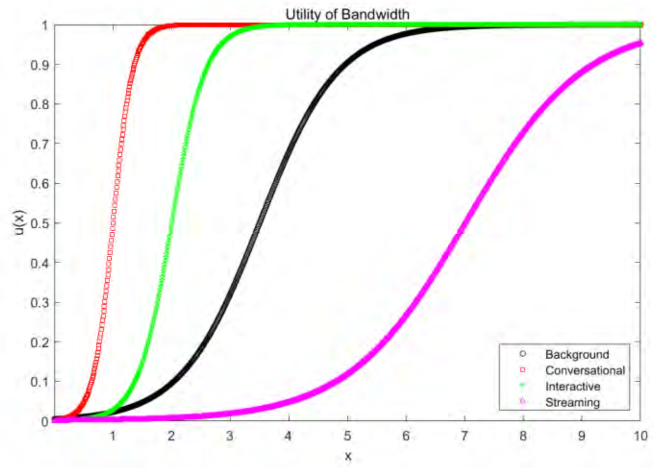

Figure 4.3. Examples of Curves for Utility Functions of Bandwidth

In the design of the network selection algorithm, there are five decision parameters used in this thesis (i.e., bandwidth, jitter, delay, loss and price), and this thesis also considers four different types of services (i.e., conversational, streaming, interactive and background). Because different services have different requirements for different network attributes (for example, voice applications have certain minimum bandwidth constraints, while data applications need the bandwidth as large as possible). The same service also has different requirements for the same network attribute (for example, for video applications, standard video requires about 1 Mbps bandwidth, and high-definition video requires about 5 Mbps bandwidth). So the type and parameters of the utility function are not fixed, but can be adjusted based on different situations. In this article, due to 4 different services and 5 different network attributes, we adopted 20 different utility functions. The types and parameters of the utility function can be adjusted according to the value range of each network attribute in the simulation experiment (i.e., Table 5.1), the assumptions of the QoS requirements of each service, the user satisfaction with network attribute values and other factors.

4.3 Calculation of Weights of Network Attributes

4.3.1 Subjective Weight Calculation

The analytic hierarchy process (AHP) is a systematic and hierarchical analysis method that combines qualitative analysis and quantitative analysis [140]; however, it faces obvious disadvantages. Its measurement scaling method is a deterministic method that does not account for the fuzziness of human thought of evaluation personnel, thereby influencing the accuracy of the evaluation results. The fuzzy analytic hierarchy process (FAHP) is a theoretical method that combines the fuzzy logic theory with traditional analytic hierarchy process and fully considers the preference and fuzziness of human thought [141]. The FAHP is currently divided into two groups: the FAHP based on fuzzy numbers and the FAHP based on a fuzzy consistent matrix.

As Triangular fuzzy numbers (TFNs) can better reflect evaluation personnel's understanding of the important relationship between attributes, this thesis chooses the FAHP based on TFNs to express the elements in the judgment matrix as TFNs, and on this basis, calculates the weights of each network attribute under different services. The specific calculation steps are as follows:

Step 1: Build a Hierarchy Model.

First, a three-layer model, consisting of the target layer, criterion layer, and scheme layer, is established after examining the relationships between various access selection impacting elements. Within this model, the target layer serves as the best network, the middle layer (i.e., criterion layer) includes network attributes (i.e., bandwidth, jitter, delay, loss, price), and the scheme layer covers all candidate networks including LTE, UMTS, WiMAX and WLAN, as shown in Figure 4.4.

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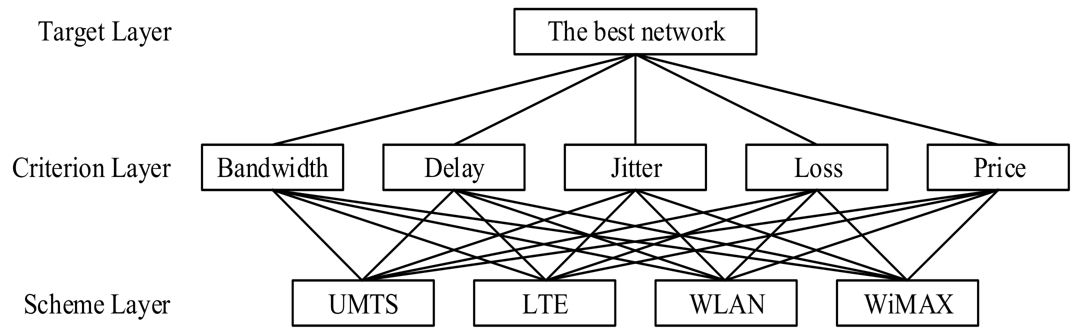

Figure 4.4. FAHP hierarchy

Step 2: Build a Judgment Matrix with TFNs.

This thesis considers four different services, each of which has different characteristics. Different network attributes, therefore, have different degrees of importance to different services. For example, the conversational service is real-time, and the typical application of this service class is voice application. As high delay and jitter will make voice calls impossible, this service class has high requirements for delay and jitter. In addition, this service class can operate well only with low bandwidth, thus having less requirements for bandwidth. The typical applications of streaming class are video on demand and live broadcasts delivered online. This service class requires higher throughput and lower price. Moreover, while the streaming class requires certain real-time guarantee, it is not as strict as the conversational service. This can maintain service continuity by setting cache, thus allowing certain packet loss ratio. The typical application of the interactive class is web browsing, which requires data interaction between the client and the server. This class requires stable jitter and a low packet loss ratio, as well as low price and bandwidth. The typical applications of the background class include e-mail or background file downloads. As such services need to run for a long time, they have higher requirements for price and bandwidth, but lower requirements for delay and jitter.

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This thesis uses the FAHP based on TFNs to calculate the weight of network attributes and uses TFNs (l, m, u) to represent the elements in the judgment matrix, where l is the lower bound value, m is the median value, and u is the upper bound value. The median value represents the most likely importance relationship between two attributes, while the upper bound value and the lower bound value represent the range of the relative importance relationship between two attributes. This thesis also determines the median value according to fuzzy scales (Table 4.2). In building the judgment matrix with TFNs, the median value of the TFNs is first determined according to the characteristics of service, followed by the upper bound value and the lower bound value, so as to determine the relative importance between two attributes. For example, the element in row 2 and column 1 of Table 4.3 indicates that the attribute delay is more important than the bandwidth (i.e., the median value is 0.8), and the importance degree ranges from 0.7 to 0.9 in the conversational service. The comparison results of importance of network attributes under different services are given from Table 4.3 to

Table 4.6.

Table 4.2
Meaning of Importance Scale

Scale	Meaning
0.5	Both are equally important
0.6	The former is slightly more important than the latter
0.7	The former is obviously more important than the latter
0.8	The former is strongly more important than the latter
0.9	The former is extremely more important than the latter
0.1, 0.2, 0.3, 0.4	If x_i is compared with x_j, r_{ij} is obtained, and x_j is compared with x_i with results in $r_{ji} = 1 - r_{ij}$.

0.55, 0.65, 0.75…	Represent the median value of adjacent grades.

Step 3: Calculate Subjective Weights of Network Attributes.

In Step 2, a complementary judgment matrix (CJM) with TFNs is obtained by comparing the importance of attributes in pairs. In this step, the weights of network attributes are calculated using the following method [142].

First, let the CJM with TFNs be A, and the element in the matrix A be a_{ij}, where $a_{ij} = (l_{ij}, m_{ij}, u_{ij})$, and i and j represent the row number and the column number of a_{ij} in the matrix, respectively. The comprehensive fuzzy value M_i^k (i.e., initial weight) of the criterion i in Layer k is calculated using Formula (4.1). In Formula (4.1), n represents the number of network attributes, which is required to determine the weight. In this thesis, $n = 5$.

$$M_i^k = \frac{\sum_{j=1}^{n} a_{ij}^k}{\sum_{i=1}^{n}\sum_{j=1}^{n} a_{ij}^k}, \quad i,j = 1,2,\dots,n \tag{4.1}$$

Then, the final weights of network attributes are obtained according to the comparison principle of fuzzy numbers. In order to explain the comparison principle of fuzzy numbers, assuming that $M_1(l_1, m_1, u_1)$ and $M_2(l_2, m_2, u_2)$ are TFNs, then the possibility degree of $M_1 \geq M_2$ is defined as Formula (4.2):

$$P(M_1 \geq M_2) = \begin{cases} 1 & m_1 \geq m_2 \\ \dfrac{l_2 - u_1}{(m_1 - u_1) - (m_2 - l_2)} & m_1 < m_2, u_1 \geq l_2 \\ 0 & otherwise \end{cases} \tag{4.2}$$

In addition, the possibility degree that one fuzzy number is greater than other m fuzzy numbers is defined as Formula (4.3):

$$d(\mathrm{M} \geq M_1, M_2, \ldots, M_m) = \min\{P(M \geq M_i)\}, i = 1,2, \ldots, \mathrm{m} \tag{4.3}$$

Finally, the values obtained above are normalized using Formula (4-4) to obtain the final weight of each attribute.

$$weight_i^{sb} = \frac{d_i}{\sum_{i=1}^{n} d_i} \tag{4.4}$$

Based on the judgment matrix with TFNs built in Step 2 and the calculation method adopted in Step 3, the weight values of network attributes are shown in Table 4.3 to Table 4.6.

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Table 4.3

Triangular Fuzzy Judgment Matrix and Network Attribute Weight for Conversational

Conversational	Bandwidth	Delay	Jitter	Loss	Price	**Weight**
Bandwidth	(0.5,0.5,0.5)	(0.1,0.2,0.3)	(0.25,0.35,0.45)	(0.3,0.4,0.5)	(0.35,0.45,0.55)	0.0390
Delay	(0.7,0.8,0.9)	(0.5,0.5,0.5)	(0.55,0.65,0.75)	(0.6,0.7,0.8)	(0.65,0.75,0.85)	0.4238
Jitter	(0.55,0.65,0.75)	(0.25,0.35,0.45)	(0.5,0.5,0.5)	(0.45,0.55,0.65)	(0.55,0.65,0.75)	0.2594
Loss	(0.5,0.6,0.7)	(0.2,0.3,0.4)	(0.35,0.45,0.55)	(0.5,0.5,0.5)	(0.5,0.6,0.7)	0.1946
Price	(0.45,0.55,0.65)	(0.15,0.25,0.35)	(0.25,0.35,0.45)	(0.3,0.4,0.5)	(0.5,0.5,0.5)	0.0833

Table 4.4

Triangular Fuzzy Judgment Matrix and Network Attribute Weight for Streaming

Streaming	Bandwidth	Delay	Jitter	Loss	Price	**Weight**
Bandwidth	(0.5,0.5,0.5)	(0.55,0.65,0.75)	(0.7,0.8,0.9)	(0.6,0.7,0.8)	(0.5,0.6,0.7)	0.3615
Delay	(0.25,0.35,0.45)	(0.5,0.5,0.5)	(0.55,0.65,0.75)	(0.45,0.55,0.65)	(0.35,0.45,0.55)	0.2061
Jitter	(0.1,0.2,0.3)	(0.25,0.35,0.45)	(0.5,0.5,0.5)	(0.3,0.4,0.5)	(0.2,0.3,0.4)	0.0231
Loss	(0.2,0.3,0.4)	(0.35,0.45,0.55)	(0.5,0.6,0.7)	(0.5,0.5,0.5)	(0.3,0.4,0.5)	0.1486
Price	(0.3,0.4,0.5)	(0.45,0.55,0.65)	(0.6,0.7,0.8)	(0.5,0.6,0.7)	(0.5,0.5,0.5)	0.2607

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Table 4.5

Triangular Fuzzy Judgment Matrix and Network Attribute Weight for Interactive

Interactive	Bandwidth	Delay	Jitter	Loss	Price	**Weight**
Bandwidth	(0.5,0.5,0.5)	(0.35,0.45,0.55)	(0.15,0.25,0.35)	(0.25,0.35,0.45)	(0.55,0.65,0.75)	0.1394
Delay	(0.45,0.55,0.65)	(0.5,0.5,0.5)	(0.25,0.35,0.45)	(0.3,0.4,0.5)	(0.6,0.7,0.8)	0.2054
Jitter	(0.65,0.75,0.85)	(0.55,0.65,0.75)	(0.5,0.5,0.5)	(0.45,0.55,0.65)	(0.65,0.75,0.85)	0.3439
Loss	(0.55,0.65,0.75)	(0.5,0.6,0.7)	(0.35,0.45,0.55)	(0.5,0.5,0.5)	(0.5,0.6,0.7)	0.2673
Price	(0.25,0.35,0.45)	(0.2,0.3,0.4)	(0.15,0.25,0.35)	(0.3,0.4,0.5)	(0.5,0.5,0.5)	0.0440

Table 4.6

Triangular Fuzzy Judgment Matrix and Network Attribute Weight for Background

Background	Bandwidth	Delay	Jitter	Loss	Price	**Weight**
Bandwidth	(0.5,0.5,0.5)	(0.6,0.7,0.8)	(0.55,0.65,0.75)	(0.5,0.6,0.7)	(0.35,0.45,0.55)	0.2823
Delay	(0.2,0.3,0.4)	(0.5,0.5,0.5)	(0.35,0.45,0.55)	(0.3,0.4,0.5)	(0.2,0.3,0.4)	0.0860
Jitter	(0.25,0.35,0.45)	(0.45,0.55,0.65)	(0.5,0.5,0.5)	(0.35,0.45,0.55)	(0.15,0.25,0.35)	0.1198
Loss	(0.3,0.4,0.5)	(0.5,0.6,0.7)	(0.45,0.55,0.65)	(0.5,0.5,0.5)	(0.25,0.35,0.45)	0.1842
Price	(0.45,0.55,0.65)	(0.6,0.7,0.8)	(0.65,0.75,0.85)	(0.55,0.65,0.75)	(0.5,0.5,0.5)	0.3277

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4.3.2 Objective Weight Calculation

In the previous section, we used FAHP method to calculate the subjective weight of network attributes. In this section, we use entropy method to calculate the objective weight of network attributes [143]. The following are the processes involved in using the entropy method to determine the objective weight of network attributes:

Step 1: Get the utility values according to the service category and the utility function of its network attributes. Then, the utility value is converted into a normalization matrix $R = (u_{ij})_{m \times n}$ (n, m are the total number of network attributes and the number of candidate networks, respectively), as shown in Formula (4.5). In this thesis, $m = 4$ and $n = 5$.

$$R = \begin{bmatrix} u_{11} & \cdots & u_{1j} & \cdots & u_{1n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ u_{i1} & \cdots & u_{ij} & \cdots & u_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ u_{m1} & \cdots & u_{mj} & \cdots & u_{mn} \end{bmatrix} \quad (4.5)$$

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Step 2: Use Formula (4.6) to determine the information entropy of each network attribute.

$$E_j = -K \sum_{i=1}^{m} u_{ij} \ln(u_{ij}) \ ,(1 \le i \le m, 1 \le j \le n) \quad (4.6)$$

In the above formula, $K = \frac{1}{\ln(m)}$.

Step 3: Use Formula (4.7) to get the objective weight of each network attribute.

$$weight_j^{ob} = \frac{1 - E_j}{\sum_{j=1}^{n}(1 - E_j)}, \qquad (1 \le j \le n) \quad (4.7)$$

The comprehensive weight of network attributes is composed of subjective weight and objective weight. Therefore, the comprehensive weight of network attribute j is as follows:

$$weight_j = \alpha \times weight_j^{ob} + (1 - \alpha) \times weight_j^{sb} \quad (4.8)$$

In Formula (4.8), the ratio of subjective and objective weights can be adjusted by setting the value of α. When $\alpha = 1$, only the objective weights of network properties are taken into account. On the other hand, when $\alpha = 0$, only the subjective weights of network properties are taken into account.

4.4 Calculation of Scores of Network Attributes

Sections 4.2 and 4.3 explained the calculation of the utility values and weights of network attributes respectively. In this section, to determine the scores of network attributes, the utility values and weights of each network attribute are employed. As fuzzy logic theory is better suited to express qualitative knowledge and experience with unclear boundaries capable of imitating the human brain's judgment on uncertainties and reasoning, it is suitable for solving uncertain and non-linear problems. Therefore, the scores of network attributes are calculated based on the fuzzy logic theory in this thesis. The calculation process mainly includes three steps: fuzzification, fuzzy inference, and defuzzification, as shown in Figure 4.5.

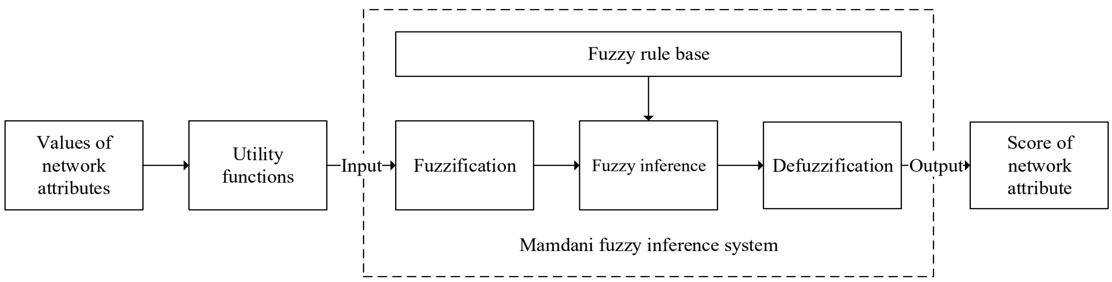

Figure 4.5. Framework for computing network attribute score based on fuzzy logic

4.4.1 Fuzzy Logic Rules Based on User Preferences

Before fuzzy inference, a fuzzy rule base must be built. In this thesis, the form of fuzzy rules is: IF (satisfying a set of conditions) THEN (deducing a conclusion). The precondition of fuzzy rules is the combination of fuzzy sets of each network attribute, and the conclusion of fuzzy rules is the fuzzy set of candidate network scores (for example, IF (bandwidth is medium, delay is high, jitter is low, packet loss ratio is medium, and price is high) THEN (network score is medium)). Since there are four types of services in this thesis, four different rule bases are built. Since there are five input linguistic variables (i.e., bandwidth, delay, jitter, loss, and price), each input linguistic variable contains three fuzzy sets (i.e., low, medium, and high), each rule corresponds to a combination of fuzzy sets of different input linguistic variables, and each rule base contains $3^5 = 243$ rules. In addition, as different services have different characteristics and each network attribute has different weight values under different services, a fuzzy rule base is built based on the network attribute weights. The specific building method is as follows.

First, different fuzzy sets and their corresponding scales are defined as Table 4.7.

Table 4.7

Fuzzy Sets and Their Corresponding Scales

Fuzzy set	**Scale**
Low（L）	1
Medium（M）	2
High（H）	3

Then, according to Formula (4.9), the scale corresponding to the fuzzy set of each network attribute is multiplied by its weight, and the Sum is obtained.

$$Sum = \sum Weight_{attribute} \times Scale \tag{4.9}$$

Finally, using Formula (4.10), the fuzzy set to which the conclusion of the fuzzy rule belongs is determined by the value of Sum. The values of α and β in Formula (4.10) can be set dynamically. In this thesis, since the minimum and maximum values of the variable Sum are 1 and 3 respectively, we divide the range from 1 to 3 into 3 equal parts (i.e., 1 to 1.67, 1.67 to 2.33, 2.33 to 3), so the values of α and β are set to 1.67 and 2.33, respectively.

$$Conclusion = \begin{cases} L & ,Sum \in [1, \alpha] \\ M & ,Sum \in (\alpha, \beta] \\ H & ,Sum \in (\beta, 3] \end{cases} \tag{4.10}$$

For example, the weights of bandwidth, delay, jitter, loss, and price are 0.0390, 0.4238, 0.2594, 0.1946, and 0.0833, respectively, under the conversational service (Table 4.3). Assuming that the precondition of fuzzy rules is IF (bandwidth is low, delay is low, jitter is medium, loss is high, and price is low), then according to Formula (4.9), the value of Sum is obtained, which is 1.65, then according to Formula (4.10), the conclusion of fuzzy rules is obtained: THEN (score is low). Examples of fuzzy rules under different service classes are shown in Table 4.8 to Table 4.11.

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Table 4.8

Example of Fuzzy Rules for Conversational

IF					THEN
Bandwidth	Delay	Jitter	Loss	Price	Score
L	M	H	H	L	M
L	H	L	L	M	M
L	H	L	H	H	H
M	L	M	L	H	L
M	M	L	M	L	L
M	M	L	H	H	M
M	H	L	M	H	M
H	L	L	L	M	L
H	M	L	L	H	M
H	H	L	M	H	M

Table 4.9

Example of Fuzzy Rules for Streaming

IF					THEN
Bandwidth	Delay	Jitter	Loss	Price	Score
L	M	H	H	L	L
L	H	L	L	M	M
L	H	L	H	H	M
M	L	M	L	H	M
M	M	L	M	L	M
M	M	L	H	H	H
M	H	L	M	H	H
H	L	L	L	M	M
H	M	L	L	H	H
H	H	L	M	H	H

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Table 4.10

Example of Fuzzy Rules for Interactive

IF					THEN
Bandwidth	Delay	Jitter	Loss	Price	Score
L	M	H	H	L	H
L	H	L	L	M	L
L	H	L	H	H	M
M	L	M	L	H	L
M	M	L	M	L	L
M	M	L	H	H	M
M	H	L	M	H	M
H	L	L	L	M	L
H	M	L	L	H	L
H	H	L	M	H	M

Table 4.11

Example of Fuzzy Rules for Background

IF					THEN
Bandwidth	Delay	Jitter	Loss	Price	Score
L	M	H	H	L	M
L	H	L	L	M	L
L	H	L	H	H	M
M	L	M	L	H	M
M	M	L	M	L	L
M	M	L	H	H	H
M	H	L	M	H	M
H	L	L	L	M	M
H	M	L	L	H	M
H	H	L	M	H	H

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4.4.2 Network Attribute Score Calculation

After constructing the fuzzy rule bases, we obtain the scores of the network attributes through three steps of fuzzification, fuzzy inference and defuzzification.

Step 1: Fuzzification.

The process of fuzzification involves turning an input item's precise value (i.e., the utility value of a network attribute) into the corresponding fuzzy linguistic variable value. The fuzzy linguistic variable value is a fuzzy set. This thesis divides the fuzzy sets into “low”, “medium”, and “high”, and are represented by low (L), medium (M), and high (H), respectively. The fuzzification step facilitates the transition from exact values to fuzzy sets. The purpose of fuzzification is to prepare for subsequent fuzzy inference operations. In addition, to convert a determined value of an input item into a fuzzy set, a membership function is required. The triangular membership function, the bell membership function, the trapezoidal membership function, the gaussian membership function, etc. are examples of commonly used membership functions. This thesis uses the triangular membership function, as shown in Figure 4.6.

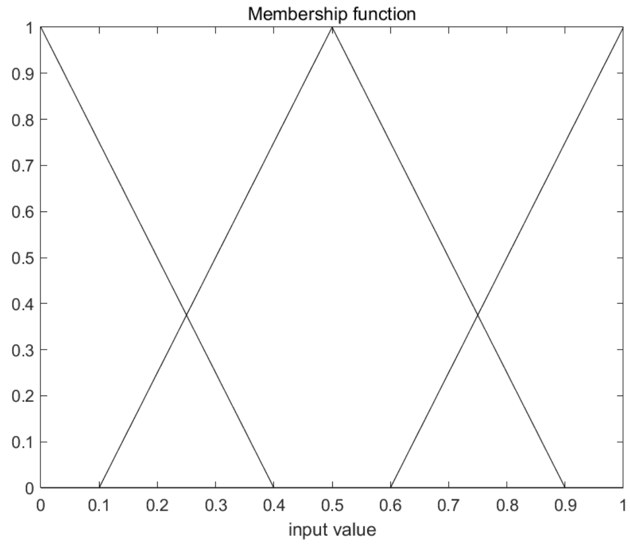

Figure 4.6. Triangular membership function

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Step 2: Fuzzy Inference.

The fuzzy rule in this thesis is the one with five inputs and one output. For convenience of explanation, the five input items (i.e., bandwidth, delay, jitter, packet loss ratio, and price) are represented by the letters "b", "d", "j", "l", and "p", while the output item (i.e., score) is represented by the letter "s". The form of rules can be expressed as:

$$\text{IF}(b \text{ is } B_i \text{ and } d \text{ is } D_i \text{ and } j \text{ is } J_i \text{ and } l \text{ is } L_i \text{ and } p \text{ is } P_i)\text{THEN}(s \text{ is } S_i)$$

The fuzzy implication relation R_i of the above rules is defined as:

$$R_i = (B_i \text{ and } D_i \text{ and } J_i \text{ and } L_i \text{ and } P_i) \rightarrow S_i \tag{4.11}$$

namely:

$$\mu_{R_i} = \left[\mu_{B_i}(b)\ and\ \mu_{D_i}(d)\ and\ \mu_{J_i}(j)\ and\ \mu_{L_i}(l) and\ \mu_{P_i}(p)\right] \rightarrow \mu_{S_i}(s) \tag{4.12}$$

This thesis is based on Mamdani's fuzzy inference method, so the fuzzy relation of the above rules is shown in Formula (4.13), in which ∧ is fuzzy AND operation, and the commonly used AND operation is the minimum operation.

$$\left[\mu_{B_i}(b) \wedge \mu_{D_i}(d) \wedge \mu_{J_i}(j) \wedge \mu_{L_i} l \wedge \mu_{P_i}(p)\right] \wedge \mu_{S_i}(s) \tag{4.13}$$

There are 243 rules in the rule base of each service in this thesis, and these fuzzy rules can be written in the form of union in the inference process, so the total fuzzy implication relation obtained is:

$$R = \bigcup_{i=1}^{243} R_i \tag{4.14}$$

After obtaining the fuzzy relation contained in the rule base, assuming that there are new inputs B', D', J', L', and P', then the output under the new inputs can be obtained according to Formula (4.15) as follows:

$$S' = (B' \; and \; D' \text{ and } J' \text{ and } L' \text{ and } P') \circ R \tag{4.15}$$

Step 3: Defuzzification.

After completing the construction of the fuzzy rule library and fuzzy inference, in the above steps, a fuzzy rule base is built and fuzzy sets of conclusions are obtained according to the fuzzy rules. In this step, the fuzzy set of conclusions is transformed into an exact value (i.e., the exact score of network attribute) through defuzzification. Commonly used defuzzification methods include the mean of maximum method (MOM) and the center of area method (COA). The defuzzification method adopted in this thesis is the COA method, which is shown as follows:

$$Score_{attribute} = \frac{\sum_{j=1}^{n} s_j \cdot \mu_{S'}(s_j)}{\sum_{j=1}^{n} \mu_{S'}(s_j)} \tag{4.16}$$

In the above formula, n is the number of elements in the domain of discourse, s_j is the j single-point fuzzy value in domain of discourse, and $\mu_{S'}(s_j)$ is the membership degree corresponding to s_j.

For example, the fuzzy set of network attribute score we obtained in the previous step is:

$$S' = \frac{0}{0} + \frac{0.25}{0.1} + \frac{0.5}{0.2} + \frac{0.75}{0.3} + \frac{1}{0.4} + \frac{0.75}{0.5} + \frac{0.5}{0.6} + \frac{0.25}{0.7} + \frac{0}{0.8} + \frac{0}{0.9} + \frac{0}{1} \tag{4.17}$$

Then, according to formula (4.16), we can get:

$$Score_{attribute} = \frac{0 \times 0 + 0.1 \times 0.25 + 0.2 \times 0.5 + \cdots + 1 \times 0}{0 + 0.25 + 0.5 + 0.75 + 1 + 0.75 + \cdots + 0} \tag{4.18}$$

Finally, by calculating the above formula, we can get the exact value of the network attribute score is 0.4.

4.5 Calculation of User Preference Value

As users have different preferences for different networks when running different services, in this section, user preference values are quantified using the FAHP method. According to the FAHP hierarchy (Figure 4.4) constructed in Section 4.3.1, the ranking of the lowest layer (i.e., the candidate network) must be calculated relative to the highest layer (i.e., the best network) in the FAHP hierarchy, as to calculate the user preference values for candidate networks. The following three steps make up the primary division of the computation process:

Step 1: In Section 4.3.1, the weights of network attributes under various services are calculated using the FAHP method, and the weights of the middle layer (i.e., network attributes) are ranked to the highest layer (i.e., the best network). According to the weight vectors obtained (Table 4.3 to Table 4.6), a relation matrix of weights of network attributes is built under different services, as shown in Table 4.12.

Step 2: This step compares the importance of the lowest layer (i.e., candidate networks) to the middle layer (i.e., network attributes) in pairs, constructs a triangular fuzzy judgment matrix, and calculates its weight according to Formulas (4.1) to (4.4), as shown in Table 4.13 to Table 4.17. According to the weight vectors in Table 4.13 to Table 4.17, the relationship matrix between different network attributes and candidate networks is constructed, as shown in Table 4.18.

Table 4.12

Subjective Weights of Network Attributes for Different Services

	Bandwidth	Delay	Jitter	Loss	Price
Conversational	0.0390	0.4238	0.2594	0.1946	0.0833
Streaming	0.3615	0.2061	0.0231	0.1486	0.2607
Interactive	0.1394	0.2054	0.3439	0.2673	0.0440
Background	0.2823	0.0860	0.1198	0.1842	0.3277

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Table 4.13

Triangular Fuzzy Judgment Matrix and Weights of Bandwidth Attribute

Bandwidth	UMTS	LTE	WLAN	WiMAX	Weight
UMTS	(0.5,0.5,0.5)	(0.5,0.6,0.7)	(0.2,0.3,0.4)	(0.15,0.25,0.35)	0.1355
LTE	(0.3,0.4,0.5)	(0.5,0.5,0.5)	(0.45,0.55,0.65)	(0.25,0.35,0.45)	0.1878
WLAN	(0.6,0.7,0.8)	(0.35,0.45,0.55)	(0.5,0.5,0.5)	(0.35,0.45,0.55)	0.2859
WiMAX	(0.65,0.75,0.85)	(0.55,0.65,0.75)	(0.45,0.55,0.65)	(0.5,0.5,0.5)	0.3908

Table 4.14

Triangular Fuzzy Judgment Matrix and Weights of Delay Attribute

Delay	UMTS	LTE	WLAN	WiMAX	Weight
UMTS	(0.5,0.5,0.5)	(0.6,0.7,0.8)	(0.55,0.65,0.75)	(0.5,0.6,0.7)	0.3928
LTE	(0.2,0.3,0.4)	(0.5,0.5,0.5)	(0.5,0.6,0.7)	(0.3,0.4,0.5)	0.1887
WLAN	(0.25,0.35,0.45)	(0.3,0.4,0.5)	(0.5,0.5,0.5)	(0.2,0.3,0.4)	0.0999
WiMAX	(0.3,0.4,0.5)	(0.5,0.6,0.7)	(0.6,0.7,0.8)	(0.5,0.5,0.5)	0.3185

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Table 4.15

Triangular Fuzzy Judgment Matrix and Weights of Jitter Attribute

Jitter	UMTS	LTE	WLAN	WiMAX	Weight
UMTS	(0.5,0.5,0.5)	(0.3,0.4,0.5)	(0.5,0.6,0.7)	(0.55,0.65,0.75)	0.3116
LTE	(0.5,0.6,0.7)	(0.5,0.5,0.5)	(0.6,0.7,0.8)	(0.65,0.75,0.85)	0.4462
WLAN	(0.3,0.4,0.5)	(0.2,0.3,0.4)	(0.5,0.5,0.5)	(0.45,0.55,0.65)	0.1618
WiMAX	(0.25,0.35,0.45)	(0.15,0.25,0.35)	(0.35,0.45,0.55)	(0.5,0.5,0.5)	0.0804

Table 4.16

Triangular Fuzzy Judgment Matrix and Weights of Loss Attribute

Loss	UMTS	LTE	WLAN	WiMAX	Weight
UMTS	(0.5,0.5,0.5)	(0.3,0.4,0.5)	(0.45,0.55,0.65)	(0.55,0.65,0.75)	0.2902
LTE	(0.5,0.6,0.7)	(0.5,0.5,0.5)	(0.55,0.65,0.75)	(0.65,0.75,0.85)	0.4177
WLAN	(0.35,0.45,0.55)	(0.25,0.35,0.45)	(0.5,0.5,0.5)	(0.5,0.6,0.7)	0.2212
WiMAX	(0.25,0.35,0.45)	(0.15,0.25,0.35)	(0.3,0.4,0.5)	(0.5,0.5,0.5)	0.0709

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Table 4.17

Triangular Fuzzy Judgment Matrix and Weights of Price Attribute

Price	UMTS	LTE	WLAN	WiMAX	Weight
UMTS	(0.5,0.5,0.5)	(0.45,0.55,0.65)	(0.2,0.3,0.4)	(0.3,0.4,0.5)	0.1618
LTE	(0.35,0.45,0.55)	(0.5,0.5,0.5)	(0.15,0.25,0.35)	(0.25,0.35,0.45)	0.0804
WLAN	(0.6,0.7,0.8)	(0.65,0.75,0.85)	(0.5,0.5,0.5)	(0.5,0.6,0.7)	0.4462
WiMAX	(0.5,0.6,0.7)	(0.55,0.65,0.75)	(0.3,0.4,0.5)	(0.5,0.5,0.5)	0.3116

Table 4.18

User Preferences Value of Candidate Networks for Different Network Attributes

	UMTS	LTE	WLAN	WiMAX
Bandwidth	0.1355	0.1878	0.2859	0.3908
Delay	0.3928	0.1887	0.0999	0.3185
Jitter	0.3116	0.4462	0.1618	0.0804
Loss	0.2902	0.4177	0.2212	0.0709
Price	0.1618	0.0804	0.4462	0.3116

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Step 3: Multiply the matrix obtained in Step 1 (Table 4.12) by the matrix obtained in Step 2 (Table 4.18), and calculate the ranking of the lowest layer (i.e., candidate networks) relative to the highest layer (i.e., the best network). The user preference values for candidate networks are shown (Table 4.19).

For example, if we want to calculate the user preference value for UMTS in the conversational service, then we multiply the elements in the same position of the first-row vector of Table 4.12 (i.e., 0.0390, 0.4238, 0.2594, 0.1946, 0.0833) and the first column vector of

Table 4.18 (i.e., 0.1355, 0.3928, 0.3116, 0.2902, 0.1618), and accumulate the five products to get the user preference value for UMTS in the conversational service (i.e., the value of the first row and the first column in Table 4.19 is 0.3225).

Table 4.19

Comprehensive User preference of Candidate Networks for Different Services

	UMTS	LTE	WLAN	WiMAX
Conversational	0.3225	0.2910	0.1757	0.2108
Streaming	0.2225	0.2001	0.2769	0.3006
Interactive	0.2914	0.3336	0.1948	0.1802
Background	0.2158	0.2260	0.2956	0.2625

4.6 Calculation of Comprehensive Scores of Candidate Networks

In the above subsection, we obtained network attribute scores for each candidate network at different service classes and user preferences for each candidate network. In this subsection, based on the network attribute scores and user preference values, the MADM method is used to obtain the ranking of the comprehensive scores of candidate networks.

The typical MADM method can comprehensively evaluate and rank a group of candidate schemes according to several attributes [52]. The MADM method includes many branches, such as SAW, MEW, GRA, and TOPSIS [57, 75]. In this thesis, the TOPSIS method is utilized to determine the comprehensive scores of candidate networks according to the network attribute scores and user preference values obtained in the above subsection.

When using the TOPSIS method, candidate networks are ranked by calculating the distance from a candidate network to the optimal network and to the worst network. If a candidate network is farthest from the worst network but closest to the best network, the network will have the highest score, and vice versa. The optimal network means that the network attribute score and the user preference value are the maximum values among all candidate networks, whereas the worst network means that the network attribute score and the user preference value are the minimum values. The following procedures are specific to using the TOPSIS method to determine the comprehensive scores of candidate networks:

First, determine the optimal and worst values of network attribute scores and user preference scores among all candidate networks. As shown in Formula (4.19), the optimal value and the worst value are expressed by V_j^+ and V_j^- respectively.

$$\begin{cases} V_j^+ = \max(s_{ij}) \\ V_j^- = \min(s_{ij}) \end{cases} \tag{4.19}$$

In Formula (4.19), $i = 1,2,3,4$ (i.e., four candidate networks) and $j = 1,2$ (i.e., the network attribute score and the user preference score).

Then, calculate the distance from each candidate network to the optimal network and the worst network. In this thesis, the distance calculated is Euclidean distance. As shown in Formula (4.20), the distance from a candidate network to the optimal network is expressed as D_i^+, and the distance to the worst network is expressed as D_i^-.

$$\begin{cases} D_i^+ = \sqrt{\sum_{j=1}^{2}\left(s_{ij} - V_j^+\right)^2} \\ D_i^- = \sqrt{\sum_{j=1}^{2}\left(s_{ij} - V_j^-\right)^2} \end{cases} \tag{4.20}$$

Finally, utilizing Formula (4.21), determine the final comprehensive score for each of the candidate networks. In addition, the candidate networks are ranked by comprehensive score, and users should choose to access the network with the highest score.

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$$Score_i^{final} = \frac{D_i^-}{D_i^+ + D_i^-} \tag{4.21}$$

4.7 Summary

In this chapter, we proposed a multi-attribute access selection mechanism that supports user preferences and service characteristics in HWN. The algorithm incorporates utility theory, fuzzy logic, FAHP, and multi-attribute decision making methods. The network attribute utility value calculation module, the network attribute weight calculation module, the network attribute score calculation module, the user preference value calculation module and the candidate network comprehensive score calculation module are presented in detail, highlighting the main functions and calculation steps of each.

CHAPTER FIVE
MCASM PERFORMANCE EVALUATIONS

In the HWN environment users can move in different directions within the coverage range of various wireless network signals, and users will continuously receive decision data from different networks, such as bandwidth, delay, jitter. In addition, due to the different services running on each user terminal, the decision of access selection becomes more complex. Therefore, the performance of the access selection and the user's quality of experience in the HWN environment will be impacted by the decision to choose the best network.

In the previous chapter, we designed a new MCASM access selection mechanism. In this chapter, we will test the method. Section 5.1 describes the experimental environment and experimental parameter settings. Section 5.2 verifies and validates MCASM in static and dynamic environments. Section 5.3 evaluates and compares the performance of MCASM with other algorithms. Section 5.4 summarizes this chapter.

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5.1 Experimental Environment and Simulation Parameter Setting

This thesis uses MATLAB R2019b as the simulation platform to test and compare the algorithms discussed. In the simulation, the performance value settings for each candidate network are shown in Table 5.1, the lowest and highest values of a network attribute when it varies dynamically are represented by the values in parentheses, with the first value serving as the network attribute's default value [36, 52]. In addition, utility functions of network attributes and parameter values of these functions under different services are shown in Table 5.2.

Table 5.1

Setting of Network Attribute Values for Candidate Networks

	Bandwidth (MB/s)	Delay(ms)	Jitter(ms)	Loss(E-6%)	Price
UMTS	1 (0.5-2)	45 (20-150)	20 (15-40)	3 (2-8)	8 (3-10)
LTE	2 (0.6-4)	60 (30-200)	15 (10-30)	2 (1-5)	6 (2-9)
WLAN	3 (0.8-8)	80 (50-250)	60 (30-80)	7 (4-12)	2 (0.5-7)
WiMAX	4 (1-10)	120 (80-300)	30 (20-50)	5 (3-10)	4 (1-8)

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Table 5.2

Type of Utility Function and Parameter Value Setting of Function

	Bandwidth	Delay	Jitter	Loss	Price
Conversational	Sigmoid-2 function $a = 6,$ $b = 1$	Sigmoid-1 function $a = 50,$ $b = 5,$ $c = 5$	Sigmoid-1 function $a = 30,$ $b = 6,$ $c = 15$	Sigmoid-1 function $a = 2.5,$ $b = 5,$ $c = 1$	Exponential function $a = 1,$ $b = -1,$ $c = 0.6,$ $d = -10$
Streaming	Sigmoid-2 function $a = 1.5,$ $b = 3.5$	Sigmoid-1 function $a = 90,$ $b = 7,$ $c = 10$	Sigmoid-1 function $a = 30,$ $b = 6,$ $c = 5$	Exponential function $a = 0,$ $b = 1,$ $c = -0.5,$ $d = 0$	Sigmoid-1 function $a = 2,$ $b = 4,$ $c = 30$
Interactive	Sigmoid-2 function $a = 3.5,$ $b = 2$	Sigmoid-1 function $a = 75,$ $b = 7,$ $c = 10$	Sigmoid-1 function $a = 15,$ $b = 4,$ $c = 30$	Sigmoid-1 function $a = 3,$ $b = 7,$ $c = 1$	Sigmoid-1 function $a = 2.5,$ $b = 7,$ $c = 10$
Background	Linear function $a = 1/10,$ $b = 0$	Linear function $a = -1/300,$ $b = 1$	Sigmoid-1 function $a = 10,$ $b = 3,$ $c = 5$	Sigmoid-1 function $a = 3.5,$ $b = 6,$ $c = 1$	Linear function $a = -1/10,$ $b = 1$

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The method proposed in this thesis is compared to four other algorithms proposed in other literature, namely Utility, TFAHP, and SAW algorithms [30] (i.e., Algorithm 1), AHP and TOPSIS algorithms [59] (i.e., Algorithm 2), Utility, FAHP, Entropy, and MEW algorithms [36] (i.e., Algorithm 3), and Utility and Fuzzy Logic algorithms [80] (i.e., Algorithm 4). Among the four algorithms involved in the comparative experiment mentioned above, there is a calculation module in each algorithm that is the same as one of the calculation modules proposed in this thesis. The superiority of the algorithm is demonstrated through performance comparisons between different algorithms. For fairness, the weights of network attributes for the other four algorithms under each service are set to be the same as the proposed algorithm.

The experiment primarily consists of three sections: The experiment in the first section, which used the static network attribute's default value, focused on assessing candidate network score rankings using various algorithms. The second section is an experiment with dynamic network attribute values that primarily evaluates the average value of five network attributes across various services and the frequency with which each candidate network is chosen across various services. The third section is the algorithm performance comparison, which mainly evaluates the average user gain in various services and the quantity of network handovers under various algorithms.

5.2 Network Selection Under the Default Network Attribute Value Environment

Based on Table 5.1 and Table 5.2, the utility values of each network attribute can be calculated for different services under static network attribute values, the details are shown in Table 5.3 to Table 5.6.

Table 5.3

Utility values of attributes for conversational in default parameter settings

Conversational	Bandwidth	Delay	Jitter	Loss	Price
UMTS	0.5000	0.8944	0.9942	0.2867	0.6988
LTE	0.9975	0.6677	0.9990	0.7532	0.9093
WLAN	1.0000	0.3229	0.1899	0.0058	0.9918
WiMAX	1.0000	0.0591	0.9375	0.0303	0.9727

Table 5.4

Utility values of attributes for streaming in default parameter settings

Streaming	Bandwidth	Delay	Jitter	Loss	Price
UMTS	0.0230	0.9992	0.9827	0.2231	0.1049
LTE	0.0953	0.9942	0.9969	0.3679	0.2703
WLAN	0.3208	0.9580	0.0725	0.0302	0.9677
WiMAX	0.6792	0.5717	0.8333	0.0821	0.6522

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Table 5.5

Utility values of attributes for interactive in default parameter settings

Interactive	Bandwidth	Delay	Jitter	Loss	Price
UMTS	0.0293	0.9972	0.9047	0.5000	0.0029
LTE	0.5000	0.9795	0.9677	0.9447	0.0213
WLAN	0.9707	0.8642	0.1049	0.0026	0.9795
WiMAX	0.9991	0.2714	0.6522	0.0272	0.2714

Table 5.6

Utility values of attributes for background in default parameter settings

Background	Bandwidth	Delay	Jitter	Loss	Price
UMTS	0.1000	0.8500	0.3846	0.7160	0.2000
LTE	0.2000	0.8000	0.5970	0.9664	0.4000
WLAN	0.3000	0.7333	0.0226	0.0154	0.8000
WiMAX	0.4000	0.6000	0.1563	0.1053	0.6000

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Although the conversational service can run well without a large bandwidth, this class of services requires lower delay and jitter. The algorithm proposed in this thesis, therefore, ranks the candidate networks as UMTS>LTE>WiMAX>WLAN under the conversational service, selects UMTS as the access network, and Algorithms 1 to 4 choose LTE as the access network (Figure 5.1(a)). As the streaming service has a large demand for bandwidth and expects a lower price, it can be seen that WiMAX can provide the largest bandwidth among all candidate networks and its price is relatively low (Table 5.1). Thus, the network chosen by the proposed algorithm is WiMAX. In addition, the network chosen by Algorithm 2, Algorithm 3, and Algorithm 4 is also WiMAX, while the network chosen by Algorithm 1 is LTE (Figure 5.1(b)). LTE can provide lower jitter, packet loss ratio, and delay, so the ranking of candidate networks obtained from the running results of our algorithm is LTE>UMTS>WiMAX>WLAN. In addition, all other algorithms choose LTE as the access network (Figure 5.1(c)). The background service does not have too high requirements for delay and jitter, but the background service expects to obtain the lowest price and a certain bandwidth guarantee. Therefore, the proposed algorithm chooses WLAN as the access network. Algorithm 1, Algorithm 3, and Algorithm 4 all choose LTE as the access network, and Algorithm 2 chooses WiMAX (Figure 5.1(d)). The proposed algorithm can reasonably connect to the most suitable network for access based on the characteristics of services and user preferences (Figure 5.1).

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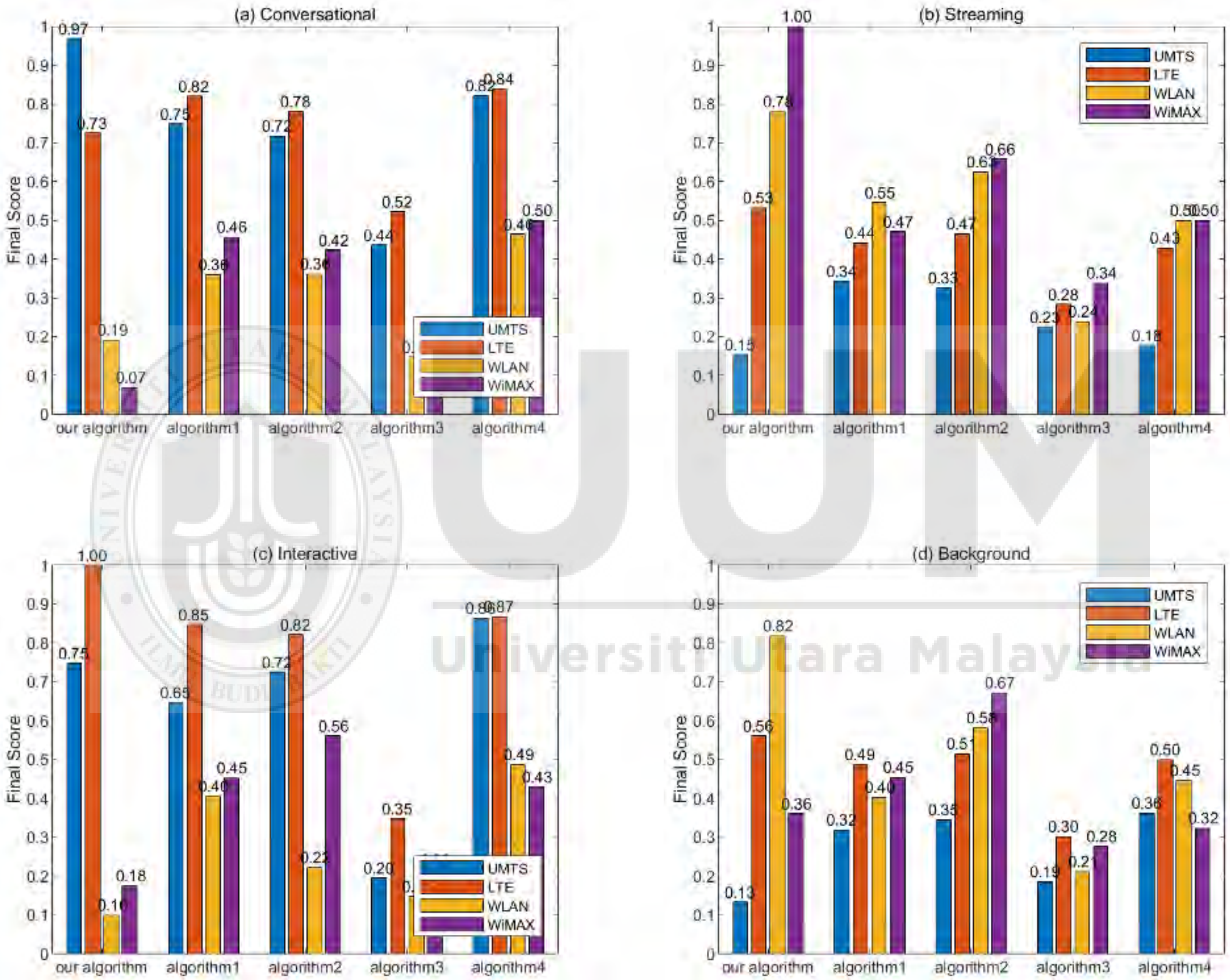

Figure 5.1. Comparison of candidate network scores under different services

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5.3 Network Selection Under Dynamic Network Attribute Value Environment

In this sub-section, the network selections made by the proposed algorithm and the other four algorithms will be evaluated under dynamically changing network attribute values (i.e., the network attribute values in Table 5.1 randomly change 1,000 times between the lowest value and the highest value in brackets). The average values of network attributes are compared when using these algorithms under different services and the number of times each candidate network is selected under different services by these algorithms.

5.3.1 Average Values of Network Attributes

In an environment where network attribute values change dynamically 1,000 times, the average bandwidth value (approx. 6 Mb/s) of the network selected by the proposed algorithm is the highest in the streaming service, followed by the background service, the interactive service, and the conversational service (Figure 5.2). The average bandwidth value for the conversational service is less than 2 MB/s. This is because from Table 4.12 above, it can be seen that among the five network attributes, the bandwidth attribute is the most important for Streaming services, while the bandwidth attribute is the least important for Conversational services. For Algorithm 1, the average bandwidth value of the network selected for streaming service and background service is basically the same. The ranking of average bandwidth values selected for Algorithm 2 for various services is the same as that for the proposed algorithm. For Algorithm 3, the average bandwidth of the network selected for streaming service and background service is higher, but neither exceeds 4 Mb/s. Algorithm 3 cannot effectively distinguish the importance of bandwidth for different services. For

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Algorithm 4, the average bandwidth value of the network selected for the background service is the largest (approx. 5 Mb/s) and the average bandwidth value for the conversational service is the smallest (approx. 2 Mb/s).

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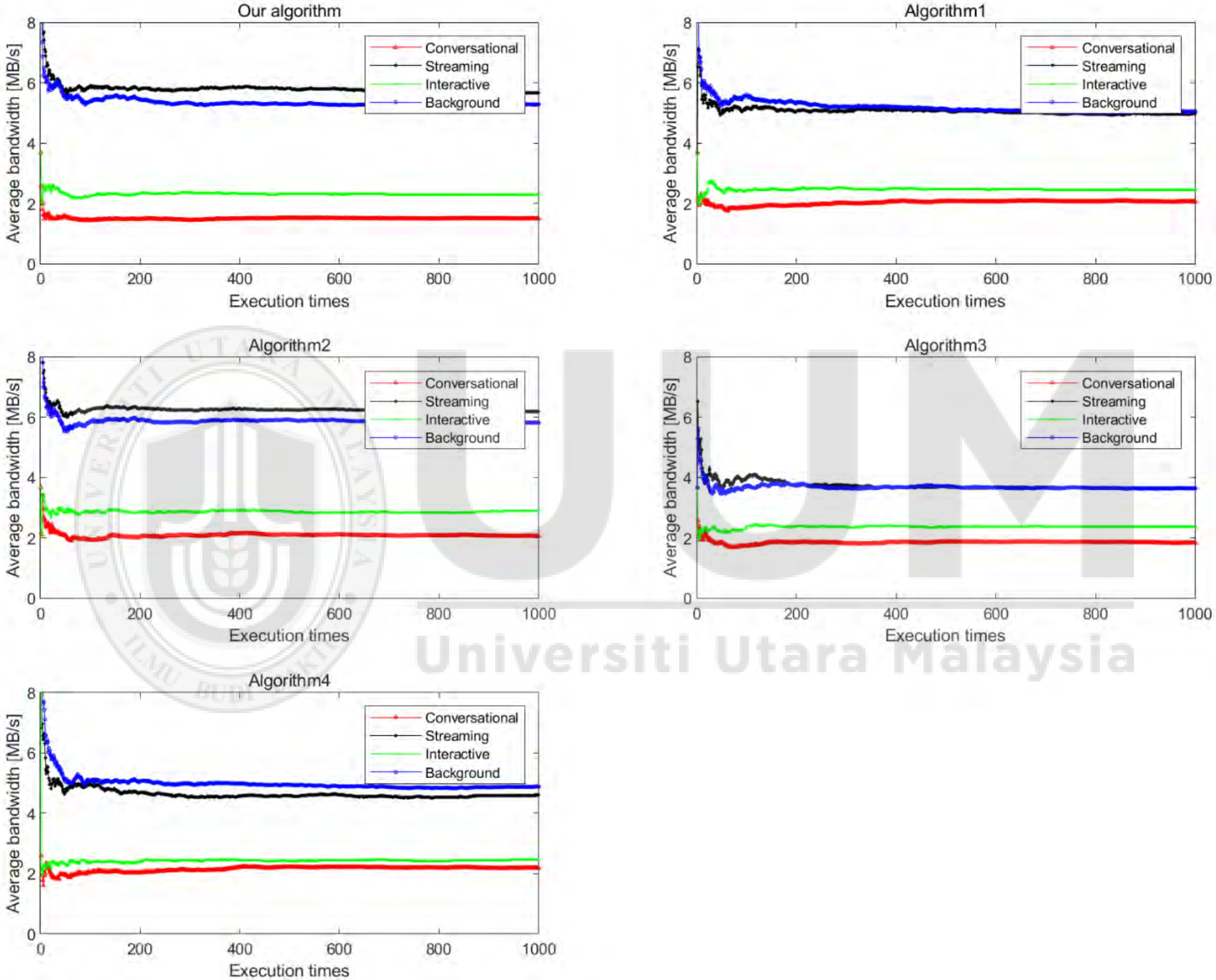

Figure 5.2. Average bandwidth of various algorithms under different services

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From Table 4.12, it can be seen that the delay attribute is the most important for conversational services. Simulation results show that the algorithm proposed in this thesis has the lowest average delay value (approx. 75 ms) for the selected network under conversational services, and the average delay of both streaming and background services exceeds 150 ms (Figure 5.3). In addition, the difference in average delay between these four services under Algorithm 1 is basically the same. In Algorithm 2, the average delay of the network selected for streaming service and background service is higher. In Algorithm 3, the average delay of the network selected for interactive service and streaming service are basically the same, and the average delay of the networks selected for these four services does not exceed 150 ms. In Algorithm 4, the average delay of interactive service and conversational service is about 100 ms.

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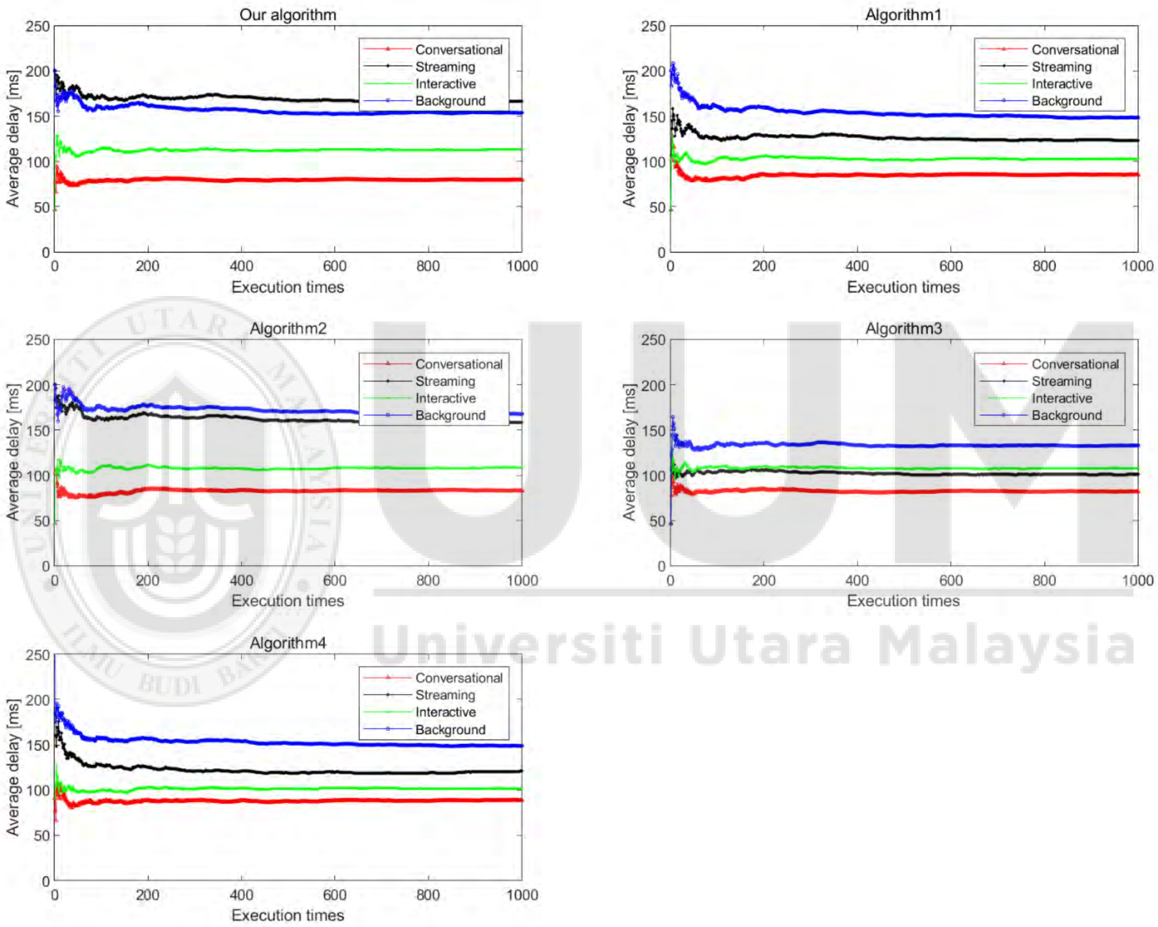

Figure 5.3. Average delay of various algorithms under different services

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Due to the importance of jitter attributes for interactive and conversational services, while jitter attributes are not important for streaming and background services, therefore, for the proposed algorithm, the average jitter of the network selected for the interactive service is the lowest (approx. 20 ms), followed by conversational service, streaming service, and background service (Figure 5. *4*). For Algorithm 1 and Algorithm 4, the average jitter for streaming service and background service is not much different (approx. 35 ms), while for Algorithm 2, the average jitter for interactive service and conversational service is not much different (approx. 23 ms). Regarding Algorithm 3, the average jitter for different services is relatively close to each other, which is in the range of 20 ms to 30 ms, Algorithm 3 has no obvious discrimination on jitter performance under various services.

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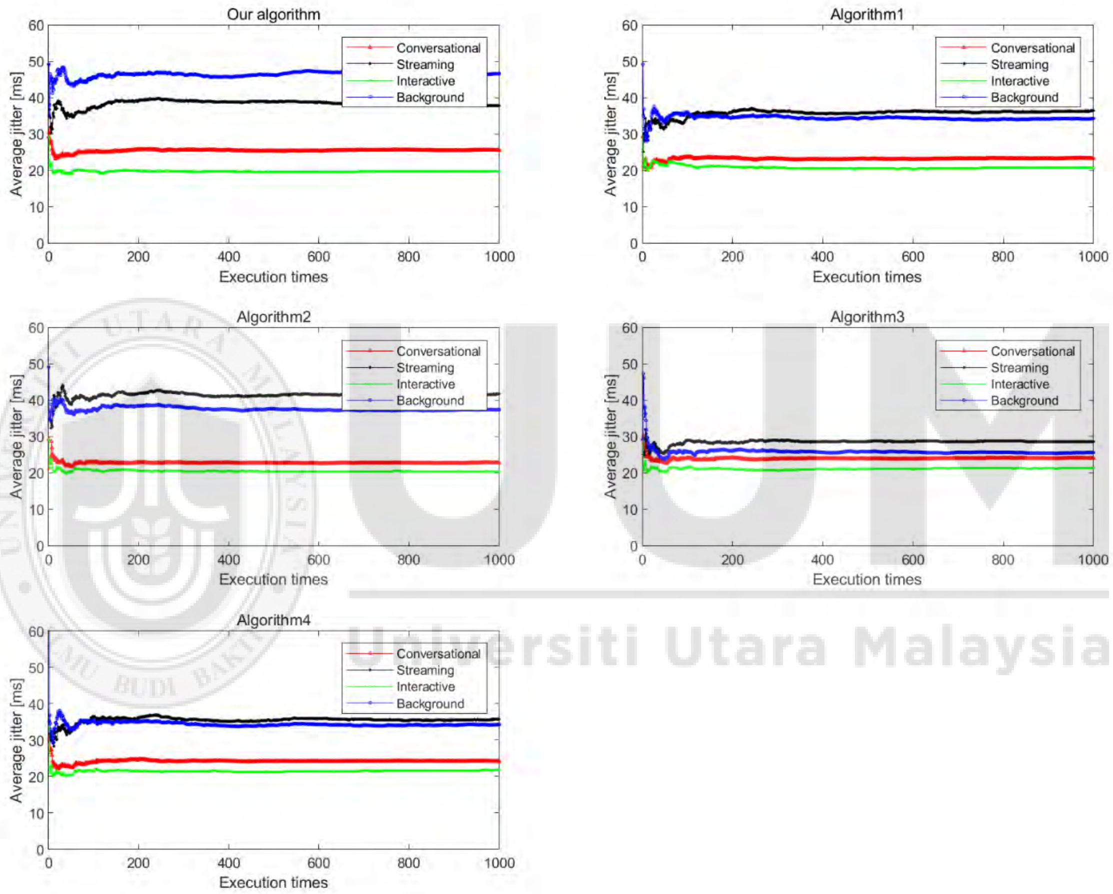

Figure 5. 4 Average jitter of various algorithms under different services

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For the algorithm proposed, the average packet loss ratio of the network selected for the interactive service is the lowest (approx. $3 \times 10^{-6}\%$), followed by the conversational service, and the average packet loss ratio for streaming service, and background service, which are higher (approx. $7 \times 10^{-6}\%$) (Figure 5.5). For Algorithm 1 and Algorithm 2, the average packet loss ratio for interactive service and conversational service are both low and do not exceed $4 \times 10^{-6}\%$. For Algorithm 3, the average packet loss ratio of the networks selected for the four services are not much different and are all in the range of $3\times 10^{-6}\%$ to $5\times 10^{-6}\%$. For Algorithm 4, the average packet loss ratio for streaming service and background service are high (approx. $6\times 10^{-6}\%$).

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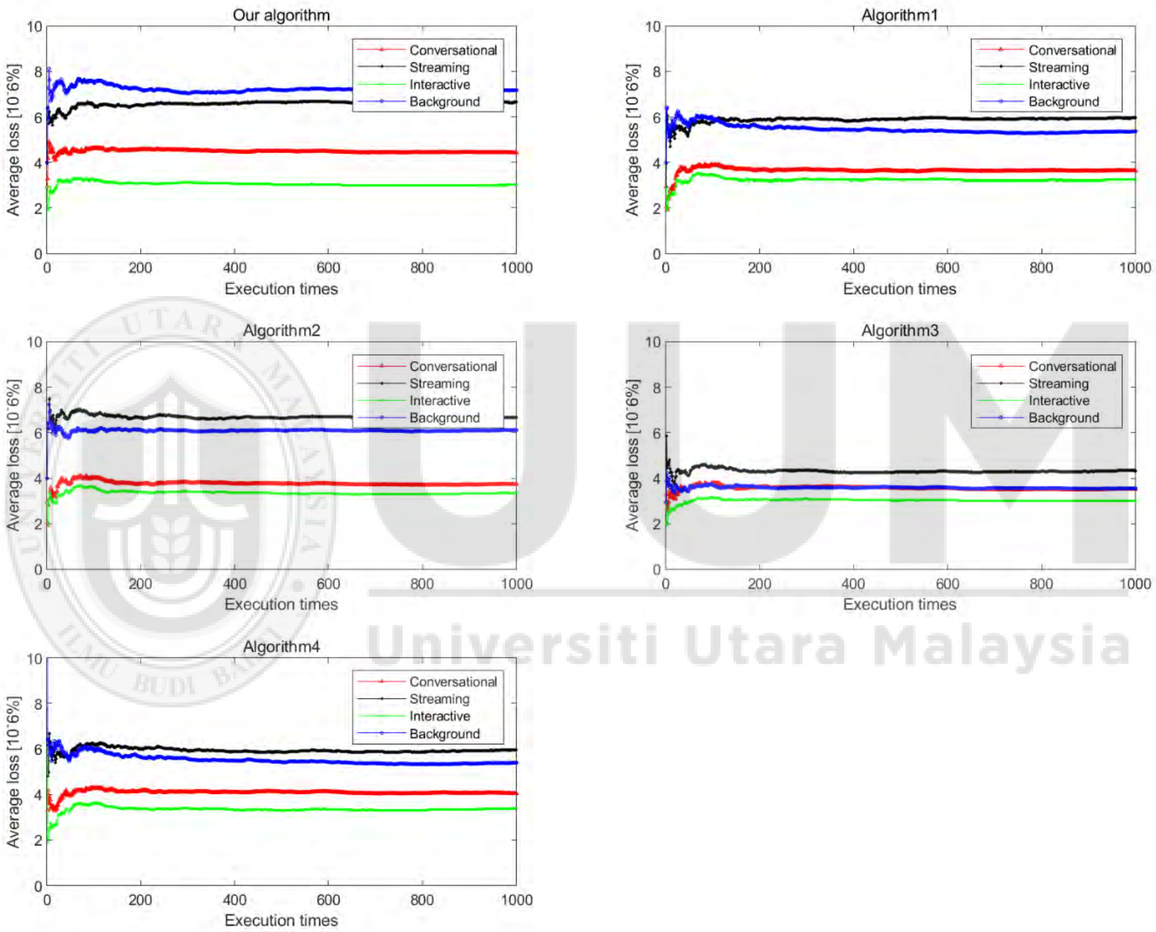

Figure 5.5. Average loss of various algorithms under different services

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For price attributes, due to the long running time of background service, background service is more eager to obtain the lowest price than the other three types of service. On the contrary, for interactive and conversational service, price is not the most important attribute. For the algorithm proposed, the average prices of the network selected for the background service is the lowest, followed by the streaming service (Figure 5.6). The average prices under the two services do not exceed 4. The average prices of networks selected for conversational service and interactive service are relatively high. For Algorithm 1 and Algorithm 4, the average prices for background service and streaming service are the same. For Algorithm 2, the average prices for conversational service and interactive service are the same. For Algorithm 3, the average prices of networks selected for the four services are in the range of 4 to 6.

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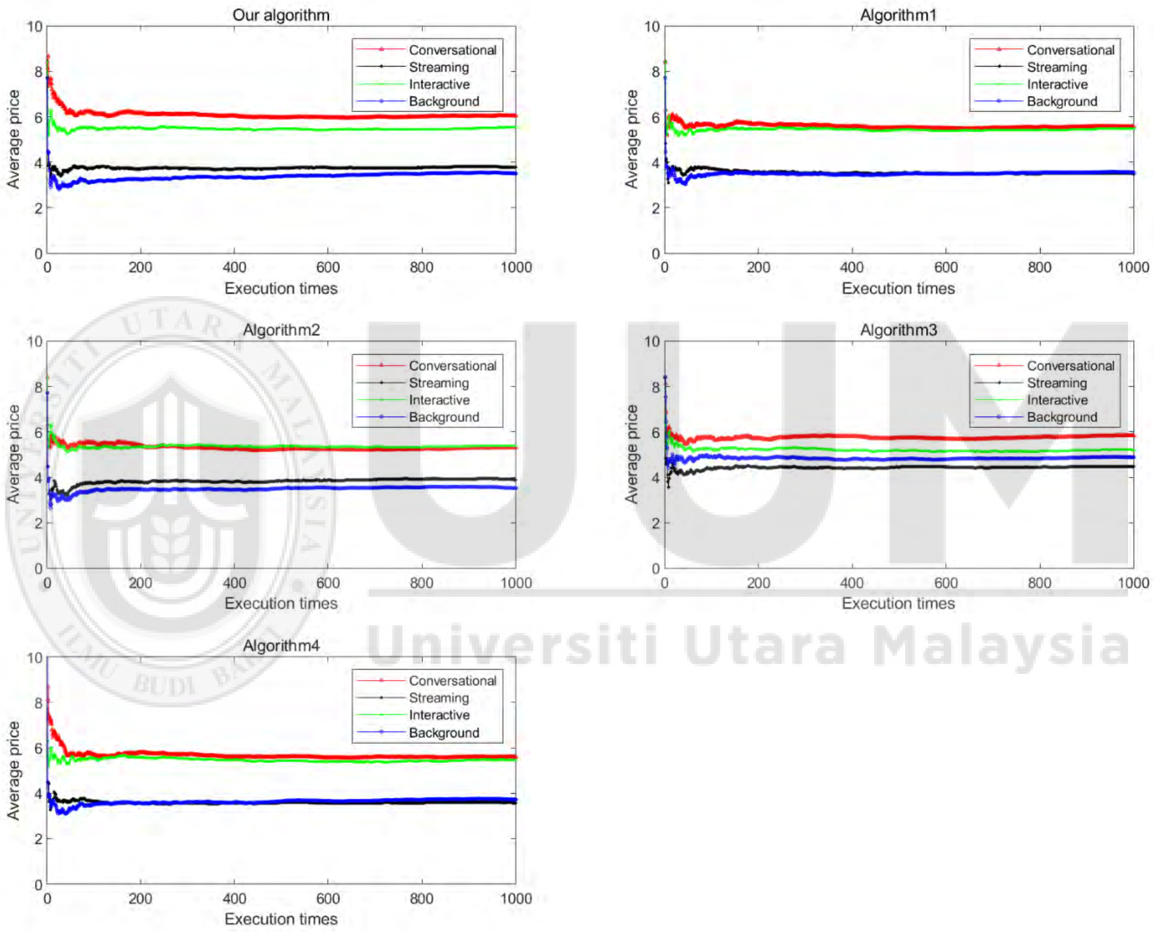

Figure 5.6. Average price of various algorithms under different services

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5.3.2 Selected Times of Each Candidate Network

Due to the sensitivity of conversational services to delay and jitter, and the fact that running this service does not require too much bandwidth. From Table 5.1 above, it can be seen that UMTS and LTE can provide lower delay and jitter than WLAN and WiMAX. In addition, the algorithm in this research includes the calculation of user preferences. As shown in Table 4.19 above, users prefer UMTS and LTE networks when running conversational services. Therefore, under the conversational service, UMTS is the network selected most often by the proposed algorithm, followed by LTE. Same with the algorithm proposed, the network most selected by Algorithm 3 is UMTS, while LTE is most selected by Algorithm 1, Algorithm 2, and Algorithm 4, followed by UMTS (Figure 5.7(a)).

For streaming services, what is required is a certain bandwidth guarantee, and the service is not sensitive to jitter and packet loss. In addition, users prefer WiMAX and WLAN networks when running streaming services. Therefore, under streaming service, WiMAX is the network most selected by the proposed algorithm, Algorithm 1, Algorithm 2, and Algorithm 4, followed by WLAN, LTE, and UMTS. Additionally, LTE is the network most selected by Algorithm 3 (Figure 5.7(b)).

For interactive services, it hopes that the network can provide lower jitter, packet loss, and delay, and that the service is not sensitive to bandwidth and price. According to the experimental environment settings, it can be seen that the LTE network can provide lower jitter, packet loss, and delay compared to the other three candidate networks, and users prefer the LTE network when running interactive services. Therefore, under the interactive service, like all other algorithms, LTE is the network most selected by the proposed algorithm, followed by UMTS (Figure 5.7(c)).

For background services, it hopes that the network can provide the lowest possible price and the highest possible bandwidth, and this service is not sensitive to delay. Due to the fact that WLAN can provide the lowest price and higher bandwidth compared to the other three candidate networks among all candidate networks. Therefore, under the background service, the network selected most by the proposed algorithm is WLAN, followed by WiMAX, which is the network selected most by Algorithm 1, Algorithm 2, and Algorithm 4, and LTE, which is the network selected most by Algorithm 3 (Figure 5.7(d)).

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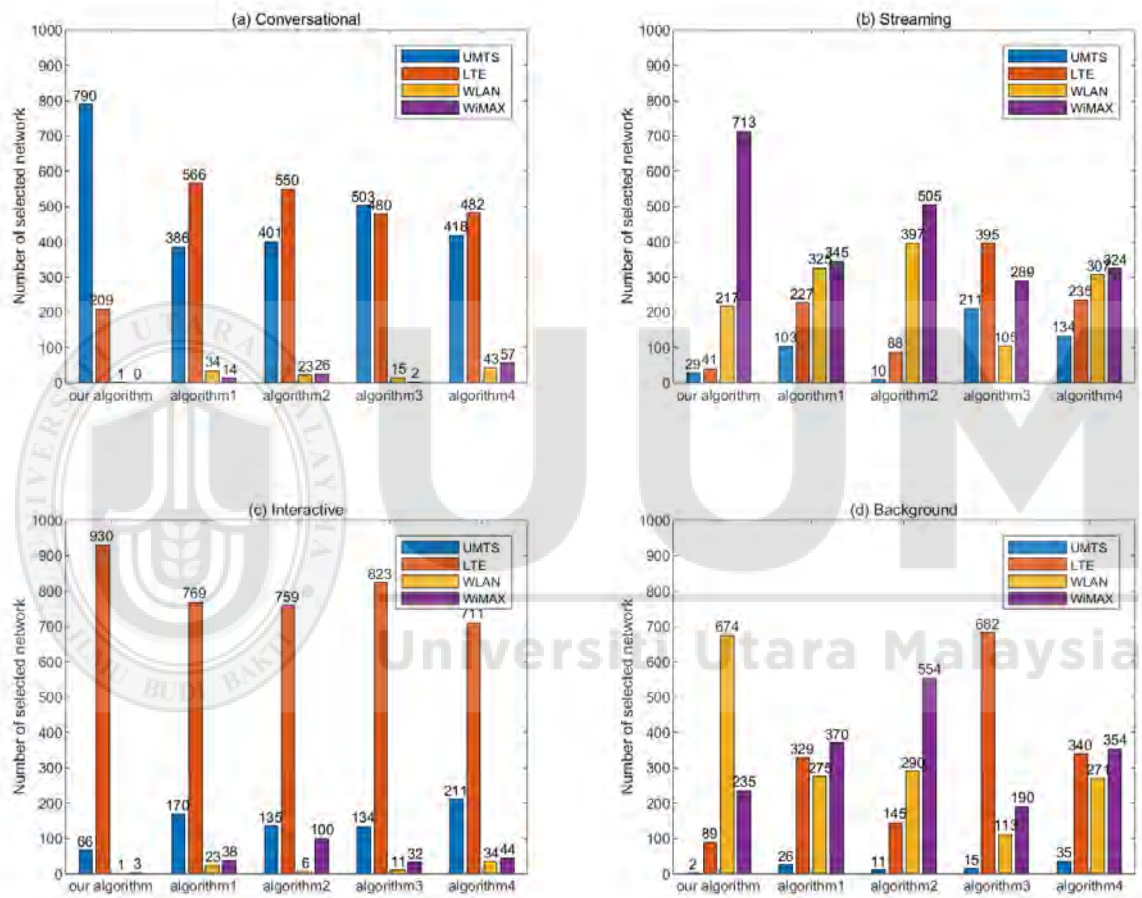

Figure 5.7. Number of candidate networks selected under different services

5.3.3 Average User Gain

In this section, we evaluate the user gain of the proposed algorithm and four other algorithms, and evaluate the network handover performance of various algorithms under different services. The definition of “Gain” proposed by Yu et al. [52] is shown in Formula (5.1):

$$G_{ij}^{s} = \lambda_{ij} \prod_{k=1}^{n} {r_{ik}}^{w_k^s} \tag{5.1}$$

In Formula (5.1), G_{ij}^{s} represents the gain obtained by switching users whose service class is s from the network i to the network j, and n is the number of network attributes. For $n = 5$ in this thesis, r_{ik} is the utility value of network attribute k in the network i, w_k^s represents the weight of network attribute k when the service class is s. In addition, for λ_{ij} in Formula (5.1), it is defined as follows:

$$\lambda_{ij} = \begin{cases} \alpha, & i = j \\ \beta, & i \neq j \end{cases} \tag{5.2}$$

In Formula (5.2), when a user selects the same network twice consecutively, let $\alpha = 1$, and when the user selects different networks twice consecutively, let $\beta = 0.8$.

The algorithm proposed in this thesis has the highest user gain, followed by Algorithm 1, Algorithm 3, and Algorithm 4 under the conversational service due to the proposed algorithm being able to select the most suitable network according to the service characteristics and user preferences, as well as avoiding handover between different networks. In addition, Algorithm 2 has the lowest user gain because Algorithm 2 does not consider the utility of the same network attribute value to different services (Figure 5.8(a)). The user gains obtained by the proposed algorithm and Algorithm 1 are higher under the streaming service, while the user gains of other algorithms are lower, but the user gains of all algorithms are relatively similar, as all algorithms under the streaming service cause more handovers between networks (Figure 5.8(b)). Under the interactive service, the user gain of the proposed algorithm is the highest, and the user gains of Algorithm 3 and Algorithm 1 are basically the same, followed by Algorithm 4 and Algorithm 2 (Figure 5.8(c)). In the background service, Algorithm 3 has the highest user gain, followed by the proposed algorithm, Algorithm 1, Algorithm 2, and Algorithm 4 (Figure 5.8(d)).

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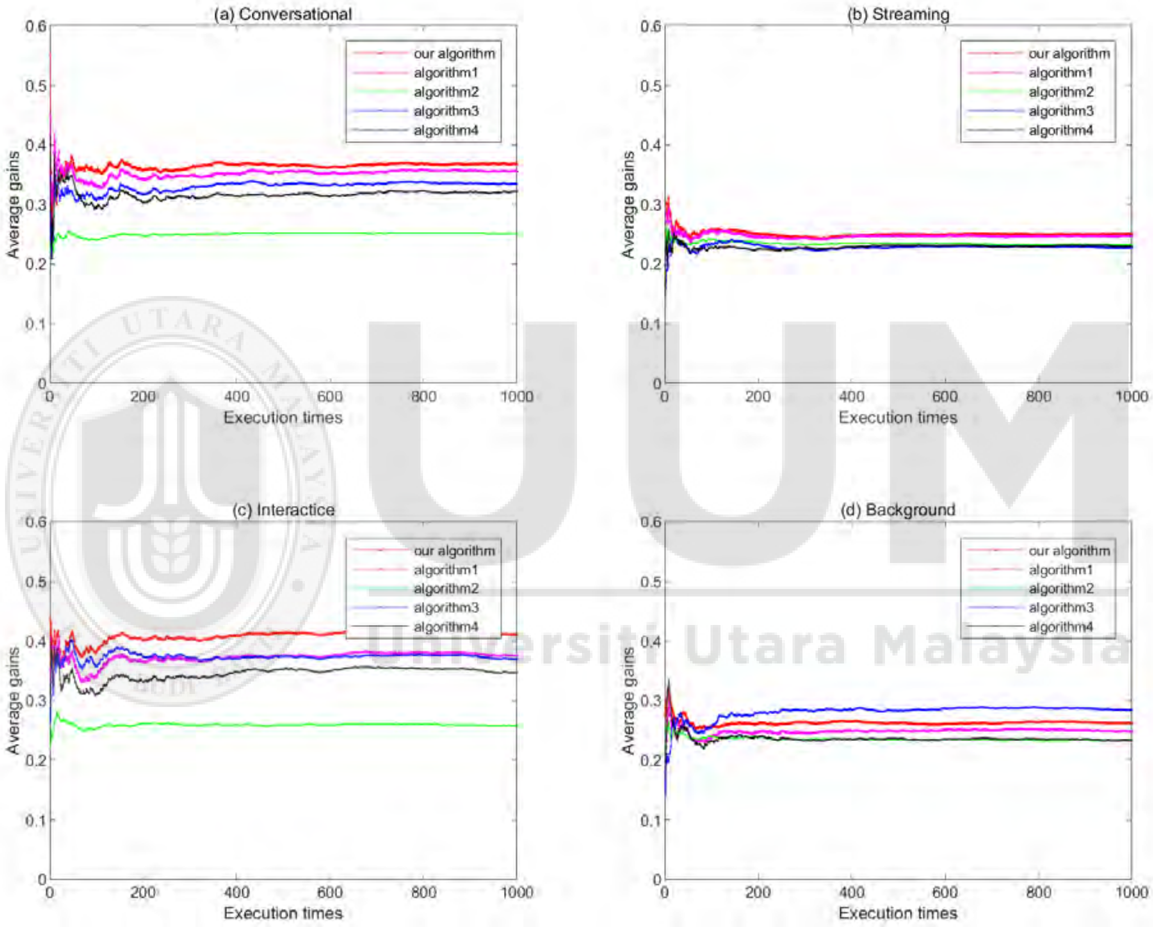

Figure 5.8. Comparison of average user gain under different services

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5.3.4 Number of Handovers Between Networks

The number of handovers between networks under different services are shown (Figure 5.9). Under the conversational service, the proposed algorithm has the lowest number of handovers between different networks (approx. 300), the number of handovers for Algorithm 1, Algorithm 2, and Algorithm 3 are basically the same (approx. 500), and the number of handovers for Algorithm 4 is the highest (approx. 600) (Figure 5.9(a)). Under the streaming service, the proposed algorithm has the lowest number of handovers (approx. 450), and Algorithms 1, 3, and 4 have more handovers (all more than 700) (Figure 5.9(b)). Under the interactive service, the number of handovers caused by the proposed algorithm is only about 150 times, followed by Algorithm 3, Algorithm 1, Algorithm 2, and Algorithm 4, and the number of handovers caused by each algorithm does not exceed 500 times (Figure 5.9(c)). The proposed algorithm and Algorithm 3 have the lowest number of handovers (approx. 500), and Algorithm 1, and Algorithm 4 have the highest number of handovers (approx. 670) under the background service (Figure 5.9(d)). Therefore, as shown in Figure 5.9, the algorithm proposed in this thesis has the lowest number of handovers in all four different services. This is because, when the network attribute scores of the candidate network are basically the same, users tend to stay connected to their preferred network, avoiding frequent switching between networks due to small changes in the performance of the candidate network.

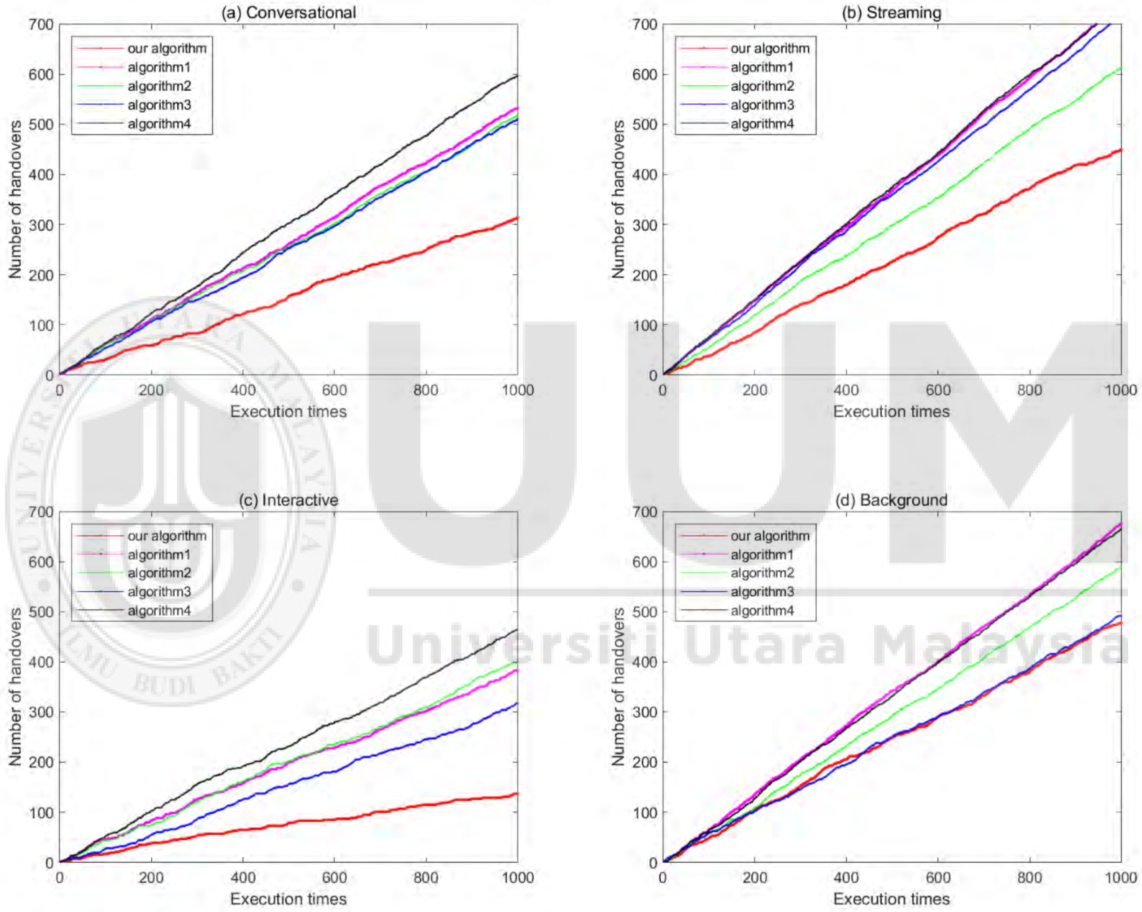

Figure 5.9. Comparison of the number of network handovers under different services

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In order to evaluate more intuitively, we use a line diagram to describe the user switching between different networks. In the process of network selection, if the user switches from network A to network B, we will draw a vertical line between network A and network B. The denser the lines in the figure, the higher the switching frequency between networks; otherwise, the rarer the lines, the fewer the times of switching between networks.

The handovers between networks caused by the proposed algorithm mainly occur between UMTS and LTE under the conversational service, users under other algorithms mainly perform network handover between UMTS and LTE, and there are also certain times of handover between WLAN and WiMAX (Figure 5.10). Under the streaming service, the handover under the proposed algorithm and Algorithm 2 mainly occurs between WiMAX and WLAN, while Algorithm 1, Algorithm 3, and Algorithm 4 all cause more handovers in the four candidate networks (Figure 5.11). Under the interactive service, the lines for the proposed algorithm are the rarest, users only have fewer handovers between UMTS and LTE, the handovers of other algorithms are mainly between UMTS and LTE, while other algorithms have a certain number of handovers between WLAN and WiMAX (Figure 5.12). Under the background service, the number of handovers of the proposed algorithm and Algorithm 3 have fewer handovers than the other three algorithms. Handovers of the four algorithms mainly occur among LTE, WLAN, and WiMAX. The lines of Algorithm 1 and Algorithm 4 are relatively denser than those of other algorithms. Algorithm 1 and Algorithm 4 cause more handovers (Figure 5.13).

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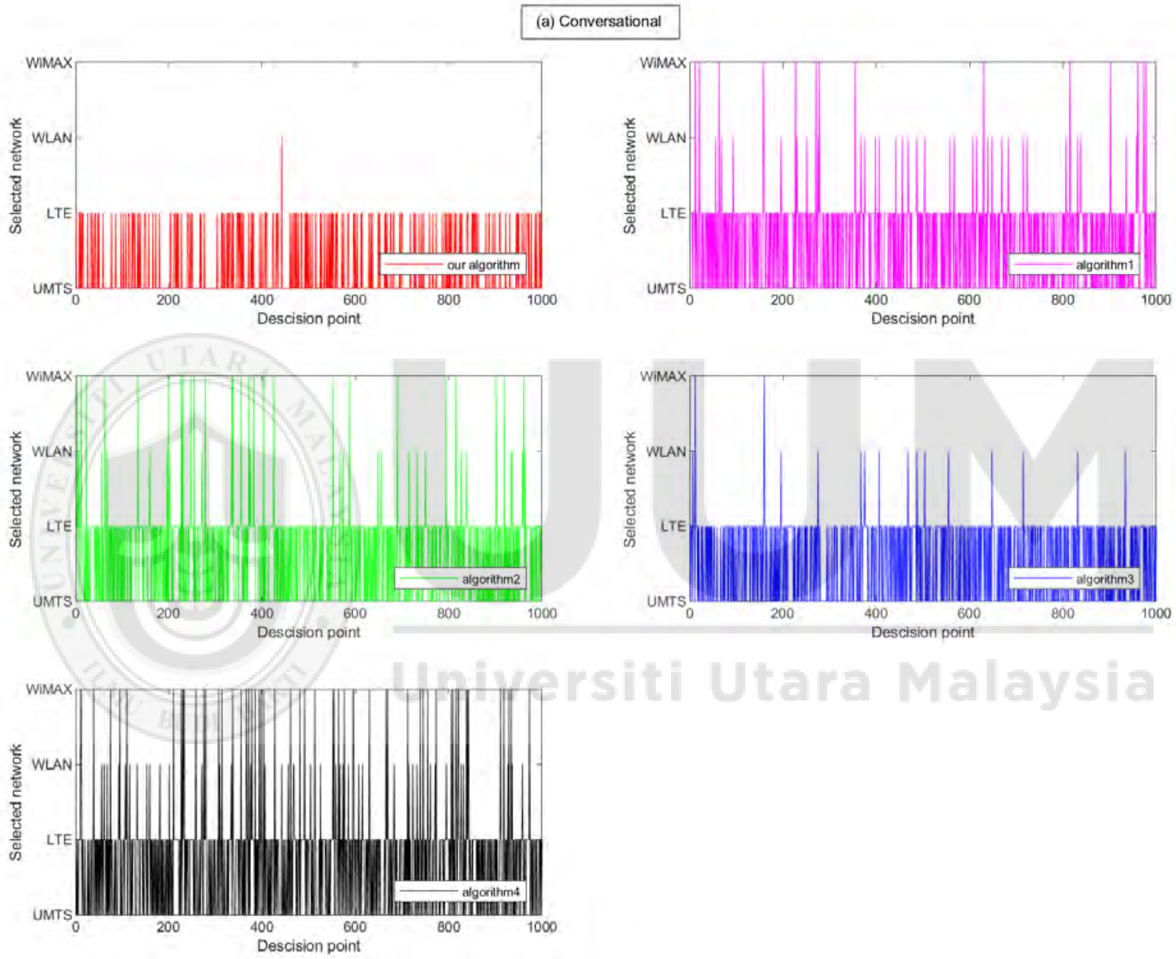

Figure 5.10. Network handovers of various algorithms under Conversational services

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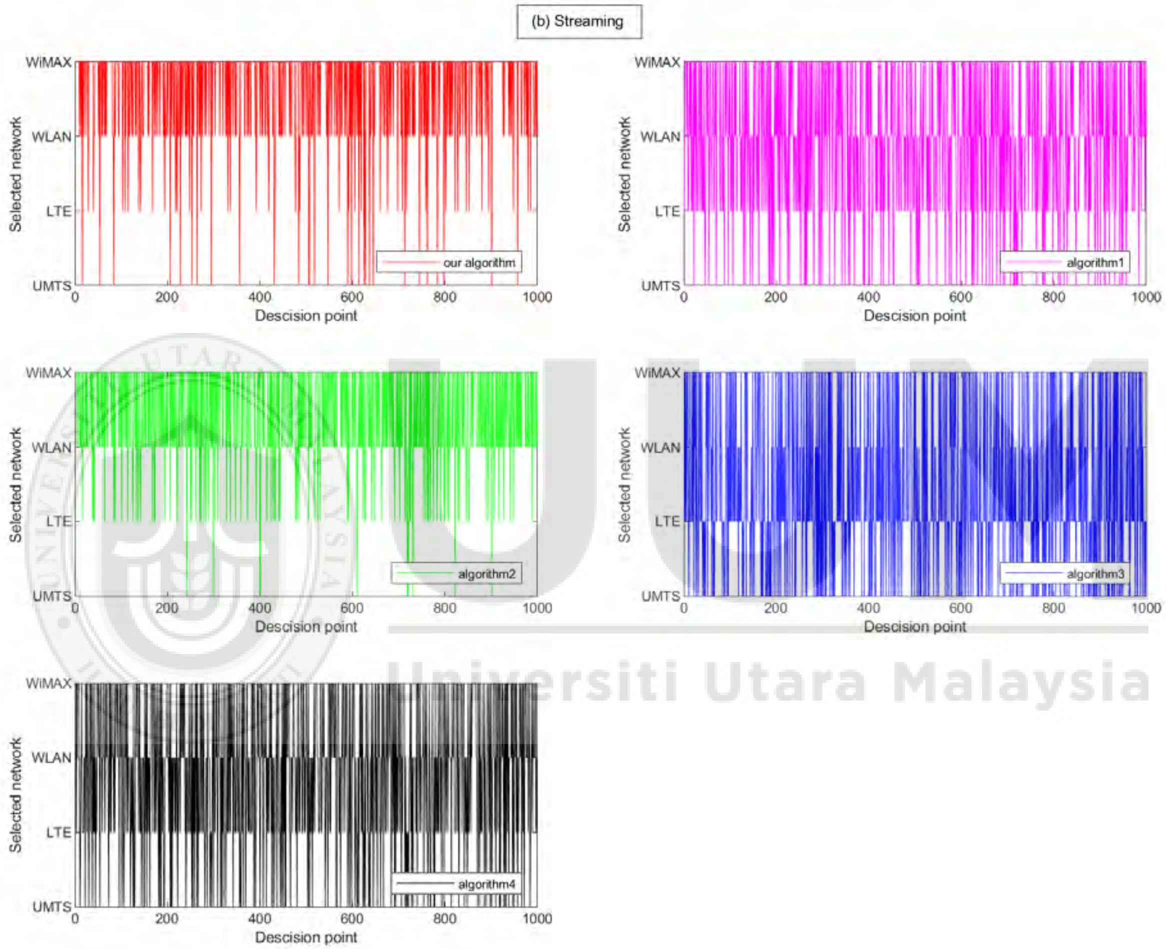

Figure 5.11. Network handovers of various algorithms under Streaming services

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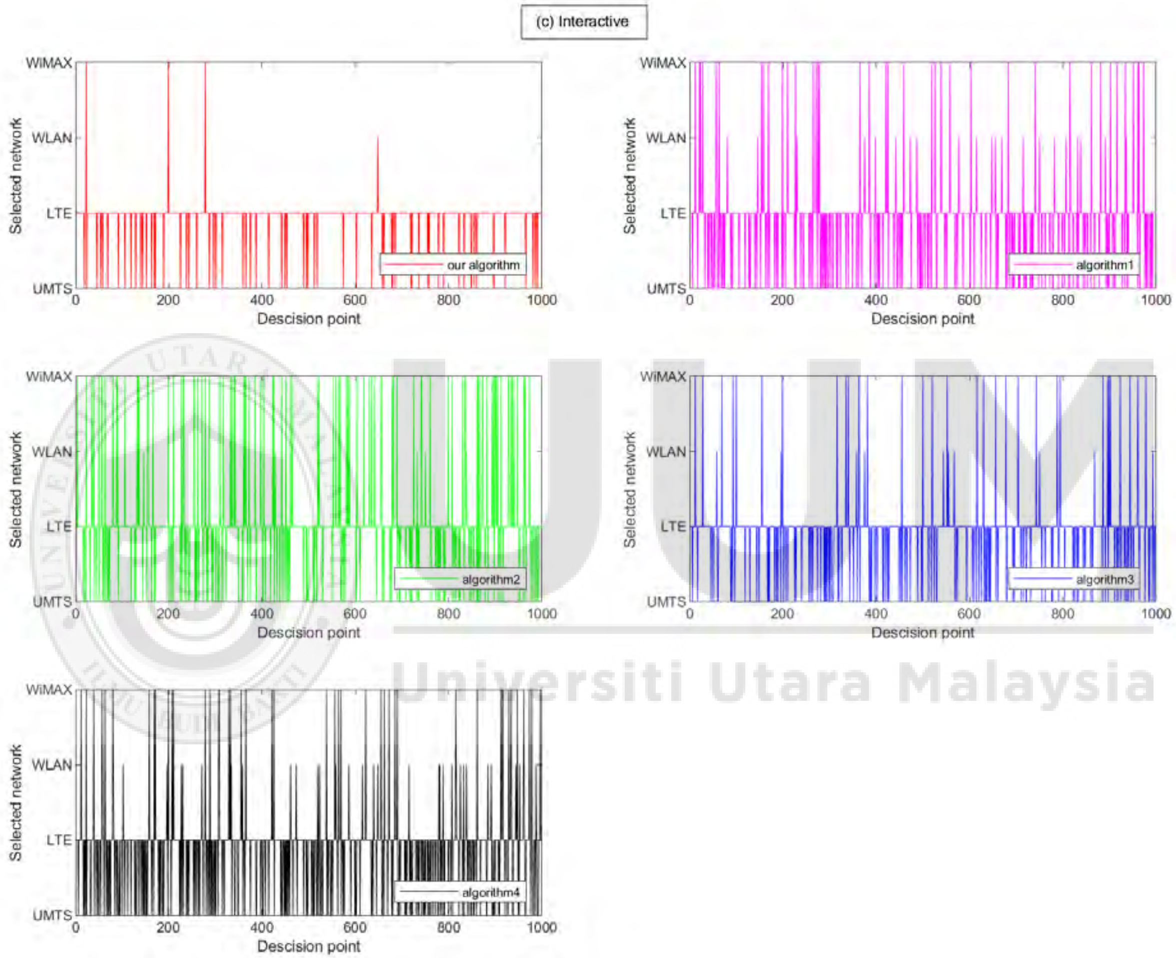

Figure 5.12. Network handovers of various algorithms under Interactive services

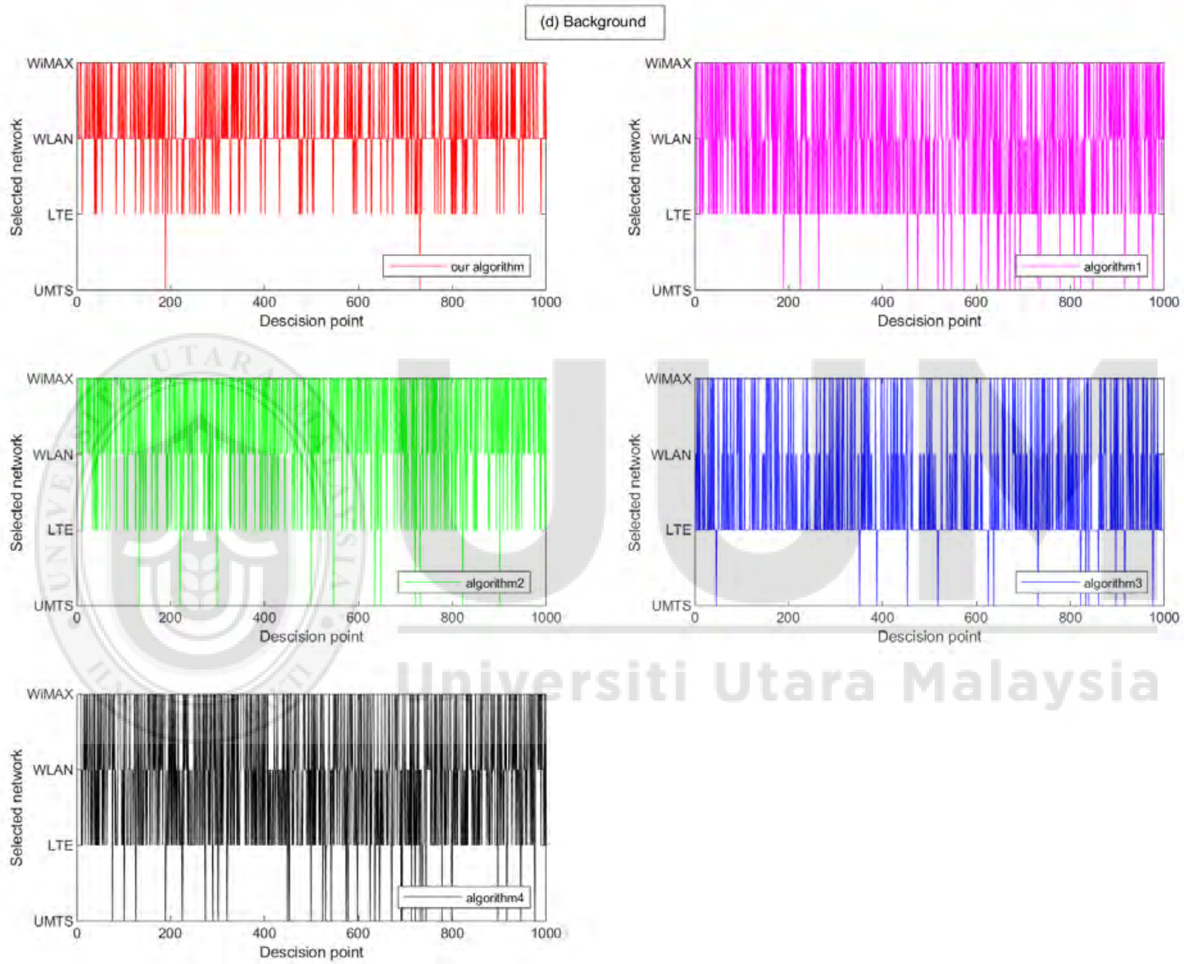

Figure 5.13. Network handovers of various algorithms under Background services

5.3.5 Number of Unnecessary Handovers Between Networks

According to the definition of "unnecessary handover" [117], the total number of handovers and unnecessary handovers of each algorithm are counted under different services. Assume that in the t time network selection, the optimal network is k (in this thesis, k can be expressed as UMTS, LTE, WLAN, WiMAX), and recorded as $BestNetwork_t = k$. When $BestNetwork_t = k$, $BestNetwork_{t+1} \neq k$, and $BestNetwork_{t+2} = k$, we call the handover caused by the $t + 1$ time network selection an unnecessary handover.

The number of unnecessary handovers between different networks by users using the proposed algorithm is 150 in the conversational service, while the number of unnecessary handovers caused by other algorithms exceed 200 times (Figure 5.14(a)). Under the streaming service, although Algorithm 1, Algorithm 3, and Algorithm 4 all have a higher total number of handovers, Algorithm 2 has the largest number of unnecessary handovers. The proposed algorithm has the lowest total number of handovers and unnecessary handovers (Figure 5.14(b)). Under the interactive service, the proposed algorithm has the least number of unnecessary handovers, which is only 67 times, followed by Algorithm 3, Algorithm 1, Algorithm 2, and Algorithm 4 (Figure 5.14(c)). Under the background service, the number of unnecessary handovers of the proposed algorithm and the other four algorithms are not much different, which is all about 200 times (Figure 5.14(d)).

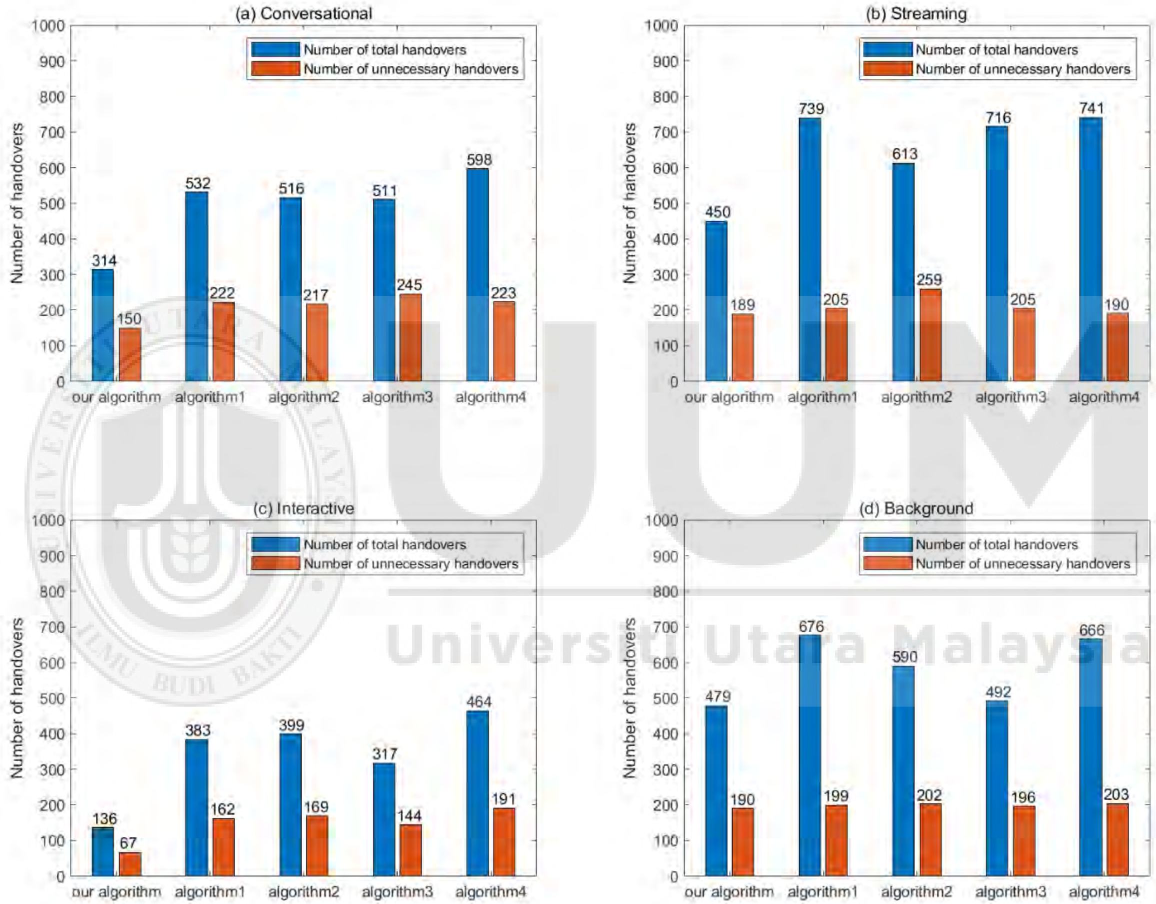

Figure 5.14. Comparison of unnecessary handovers of various algorithms under different services

5.4 Summary

In this chapter, we conducted an experimental evaluation of the algorithms proposed in Chapter Four, compare the proposed algorithms with the four algorithms proposed in other literature, and analyze the average network attribute value of the selected network, the number of candidate networks selected, the user gain, the number of handovers, and the number of unnecessary handovers of various algorithms. The simulation results show that the algorithm proposed in this thesis has better comprehensive performance than other algorithms.

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CHAPTER SIX

CONCLUSION AND FUTURE WORK

The main purpose of this research is to develop a multi-criteria access selection mechanism based on user preferences in HWN, and evaluate its performance through various simulation experiments. The conclusion of the research is presented in this chapter. Section 6.1 discusses the research findings, the significance of access selection, its potential implementation, and its advantages for HWN. The contributions made by this research are mentioned in Section 6.2. The research's limitations are then discussed in Section 6.3. Finally, Section 6.4 makes some recommendations for additional research.

6.1 Summary of the Research

The continuous development of wireless local area network, mobile cellular network, wireless metropolitan area network and other network technologies provides users with more and more high-quality network services. Due to the differences in the performance of various wireless networks and the business needs of users, any single network technology cannot meet the business needs of all users at the same time. Therefore, the wireless network environment has gradually evolved into a HWN with multiple types of networks coexisting. Access selection technology can enable users in a HWN environment to connect to the most appropriate network. It is one of the key technologies in HWN, and is also the hot and difficult point of current research.

According to Chapter 1, the main research objective of this thesis is to determine the most suitable access network among numerous candidate networks in HWN environments, and propose a multi-criteria access selection mechanism based on user preference to ensure service quality and user experience quality.

Chapter 2 gave a comprehensive overview of access selection algorithms for HWN, analyzes the process of access selection, and makes a detailed comparison of various access selection algorithms, which will help us establish a different access selection mechanism.

Chapter 3 gives a thorough explanation of the research methodology that was employed in this research to ensure the orderly execution of the research plan. We used the Design Research Methodology (DRM) to accomplish this goal. The DRM framework can be used in any area of research. The DRM assisted the researcher in creating a blueprint for implementation that covered all aspects of research, from review through assessment, in the form of a conceptual model and primary design.

In Chapter 4, a new MCASM access selection mechanism based on user preference in HWN is designed, and the calculation of utility value, weight, and score of network attributes, user preference value and comprehensive score of candidate networks are analyzed in detail to obtain the comprehensive score ranking of candidate networks.

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Finally, in Chapter 5, the algorithm proposed in Chapter 4 was simulated and compared with the other four algorithms. The simulation results demonstrate that the algorithm proposed in this thesis can enable users to access the most appropriate network, enable users to obtain higher gain and reduce user handover between different networks. The proposed algorithm is of great significance to the research of access selection.

The results of the MCASM performance evaluation confidently highlighted the fact that the research's stated objectives, as laid out in this thesis, have been fully and successfully attained.

6.2 Research Contributions

We established an analysis model for the decision of access selection to determine the best network among the candidate networks. In addition, the analysis model is transformed to measure the performance in HWN environment. The following are the specific contributions of this thesis:

i. This thesis proposed a new MCASM access selection mechanism. To the best of our knowledge, MCASM is the first mechanism that integrates utility theory, entropy method, FAHP, fuzzy logic and MADM methods.

ii. MCASM access selection mechanism can support the diversity of service characteristics and user preferences at the same time.

iii. Through simulation experiments, it has been proven that MCASM can enable users to access the most suitable network, improve the user gain, reduce the number of handovers between networks, and reduce the number of unnecessary handovers between networks.

6.3 Research Limitation

Although a set of methodologies and principles were carefully chosen and used in the conduct of this research, it nevertheless has significant limitations. First, in the real HWN environment, there are many different wireless network structures. This research is carried out under specific simulation network experimental conditions, and does not include all wireless network structures. In addition, during the operation of the network, the access nodes are dynamically increased or decreased, not fixed. This research does not consider the change of access nodes. Second, users run a variety of services. This research only considers that a user runs only one service at the same time, and doesn't account for users running multiple services simultaneously. Third, users in HWN environment accessing a certain network will have an impact on other connected users. This research does not account for how users might influence one another.

6.4 Future Works

The mechanism proposed in this research improves the performance of access selection in HWN scenarios. There are, however, some restrictions and unfinished projects that can be explored for potential future possibilities. The following are potential extensions:

i. With the continuous development of HWN, there will be more and more types of user applications that each wireless network needs to carry. Different types of applications have different constraint requirements for different QoS parameters. Therefore, when designing network selection algorithms for future HWN scenarios, how to achieve differentiated user service quality assurance becomes our next research direction.

ii. In the development of the next-generation wireless networks, the contradiction between the growing user demand and the increasingly shortage of network resources will become more and more obvious. Therefore, how to jointly optimize network resource allocation and access selection in HWN environment to further improve the utilization efficiency of network resources is a problem that needs to be explored in the future.

iii. In the HWN environment, the access selection process will have the problem of individual utility optimization and fairness between individuals. The improvement of the experience quality of one user will often lead to the utility loss of other users.

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Therefore, while designing an access selection algorithm that supports user preferences, further consideration should be given to improving fairness among users, which we also need to study further.

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REFERENCES

[1] A. Ghosh, N. Mangalvedhe, R. Ratasuk, B. Mondal, M. Cudak, E. Visotsky, T. A. Thomas, J. G. Andrews, P. Xia, H. S. Jo, H. S. Dhillon, and T. D. Novlan, "Heterogeneous Cellular Networks: From Theory to Practice," *IEEE COMMUNICATIONS MAGAZINE,* vol. 50, pp. 54-64, 2012.

[2] N. H. Mahmood, F. Yilmaz, M. Alouini, and G. E. Oien, "Heterogeneous Next-generation Wireless Network Interference Model-and Its Applications," *TRANSACTIONS ON EMERGING TELECOMMUNICATIONS TECHNOLOGIES,* vol. 25, pp. 563-575, 2014.

[3] A. Keshavarz-Haddad, E. Aryafar, M. Wang, and M. Chiang, "HetNets Selection by Clients: Convergence, Efficiency, and Practicality," *IEEE-ACM TRANSACTIONS ON NETWORKING,* vol. 25, pp. 406-419, 2017.

[4] J. N. Sun, Z. H. Qian, X. Wang, and X. Wang, "ES-DQN-Based Vertical Handoff Algorithm for Heterogeneous Wireless Networks," *IEEE WIRELESS COMMUNICATIONS LETTERS,* vol. 9, pp. 1327-1330, 2020.

[5] M. S. Ramdev, R. Bajaj and J. Sidhu, "Remote Radio Head Scheduling in LTE-Advanced Networks," *WIRELESS PERSONAL COMMUNICATIONS,* vol. 122, pp. 621-644, 2022.

[6] M. Z. Chowdhury, M. J. Rahman, G. Muntean, P. V. Trinh, and J. Carlos Cano, "Convergence of Heterogeneous Wireless Networks for 5G-and-Beyond Communications: Applications, Architecture, and Resource Management," *WIRELESS COMMUNICATIONS AND MOBILE COMPUTING,* vol. 2019, pp. 1-2, 2019.

[7] M. Yaqoob, O. Gemikonakli and E. Ever, "Modelling Heterogeneous Future Wireless Cellular Networks: An Analytical Study for Interaction of 5G Femtocells and Macro-cells," *FUTURE GENERATION COMPUTER SYSTEMS-THE INTERNATIONAL JOURNAL OF ESCIENCE,* vol. 114, pp. 82-95, 2021.

Universiti Utara Malaysia

[8] A. Desai, M. Palandoken, J. Kulkarni, G. Byun, and T. K. Nguyen, "Wideband Flexible/Transparent Connected-Ground MIMO Antennas for Sub-6 GHz 5G and WLAN Applications," *IEEE ACCESS,* vol. 9, pp. 147003-147015, 2021.

[9] O. Seijo, J. A. Lopez-Fernandez, H. P. Bernhard, and I. Val, "Enhanced Timestamping Method for Subnanosecond Time Synchronization in IEEE 802.11 Over WLAN Standard Conditions," *IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS,* vol. 16, pp. 5792-5805, 2020.

[10] W. Yin, P. Z. Hu, J. Indulska, M. Portmann, and Y. Mao, "MAC-Layer Rate control for 802.11 Networks: A Survey," *WIRELESS NETWORKS,* vol. 26, pp. 3793-3830, 2020.

[11] P. Mathur, R. Augustine, M. Gopikrishna, and S. Raman, "Dual MIMO Antenna System for 5G Mobile Phones, 5.2 GHz WLAN, 5.5 GHz WiMAX and 5.8/6 GHz WiFi Applications," *IEEE ACCESS,* vol. 9, pp. 106734-106742, 2021.

[12] H. Ghouz, M. Sree and M. A. Ibrahim, "Novel Wideband Microstrip Monopole Antenna Designs for WiFi/LTE/WiMax Devices," *IEEE ACCESS,* vol. 8, pp. 9532-9539, 2020.

[13] T. Han, Y. Yang, X. Ge, and G. Mao, "Mobile Converged Networks: Framework, Optimization, and Challenges," *IEEE WIRELESS COMMUNICATIONS,* vol. 21, pp. 34-40, 2014.

[14] A. Kakkar, "A Survey on Secure Communication Techniques for 5G Wireless Heterogeneous Networks," *INFORMATION FUSION,* vol. 62, pp. 89-109, 2020.

[15] S. Han, "Congestion-Aware WiFi Offload Algorithm for 5G Heterogeneous Wireless Networks," *COMPUTER COMMUNICATIONS,* vol. 164, pp. 69-76, 2020.

[16] E. Gures, I. Shayea, M. Sheikh, M. Ergen, and A. A. El-Saleh, "Adaptive Cell Selection Algorithm for Balancing Cell Loads in 5G Heterogeneous Networks," *ALEXANDRIA ENGINEERING JOURNAL,* vol. 72, pp. 621-634, 2023.

[17] F. A. Al Emam, M. E. Nasr and S. E. Kishk, "Context-Aware Parallel Handover

Universiti Utara Malaysia

Optimization in Heterogeneous Wireless Networks," *ANNALS OF TELECOMMUNICATIONS,* vol. 75, pp. 43-57, 2020.

[18] S. Gourdache, A. Bilami and K. Barka, "A Framework for Spectrum Harvesting in Heterogeneous Wireless Networks Integration," *JOURNAL OF KING SAUD UNIVERSITY-COMPUTER AND INFORMATION SCIENCES,* vol. 33, pp. 281-290, 2021.

[19] L. Cao, Y. G. Yue, Y. Cai, and Y. Zhang, "A Novel Coverage Optimization Strategy for Heterogeneous Wireless Sensor Networks Based on Connectivity and Reliability," *IEEE ACCESS,* vol. 9, pp. 18424-18442, 2021.

[20] Z. H. Xu, Z. Zhang, S. L. Wang, Y. Yan, and Q. Cheng, "Resource-Constraint Network Selection for IoT Under the Unknown and Dynamic Heterogeneous Wireless Environment," *IEEE INTERNET OF THINGS JOURNAL,* vol. 10, pp. 12322-12337, 2023.

[21] A. Q. Zhu, M. F. Ma, S. T. Guo, and Y. Y. Yang, "Adaptive Access Selection Algorithm for Multi-Service in 5G Heterogeneous Internet of Things," *IEEE TRANSACTIONS ON NETWORK SCIENCE AND ENGINEERING,* vol. 9, pp. 1630-1644, 2022.

[22] H. Yu, Y. Ma and J. Yu, "Network Selection Algorithm for Multiservice Multimode Terminals in Heterogeneous Wireless Networks," *IEEE ACCESS,* vol. 7, pp. 46240-46260, 2019.

[23] S. D. Roy and S. R. V. Reddy, "Signal Strength Ratio Based Vertical Handoff Decision Algorithms in Integrated Heterogeneous Networks," *WIRELESS PERSONAL COMMUNICATIONS,* vol. 77, pp. 2565-2585, 2014.

[24] G. M., H. N., P. Y. S., T. S., A. S., and K. Y., "Characterizing Performance of Load-Aware Network Selection in Multi-Radio (Wifi/LTE) Heterogeneous Networks," in *2013 IEEE Globecom Workshops (GC Wkshps)*, 2013, pp. 397-402.

[25] A. S. M., H. S. and M. A., "Utility Function-Based TOPSIS for Network Interface Selection in Heterogeneous Wireless Networks," in *2016 IEEE International*

Universiti Utara Malaysia

Conference on Communications (ICC), NEW YORK, 2016, pp. 1-6.

[26] F. Chen, J. Zhang, Z. Chen, J. Wu, and N. Ling, "Buffer-Driven Rate Control and Packet Distribution for Real-Time Videos in Heterogeneous Wireless Networks," *IEEE ACCESS,* vol. 7, pp. 27401-27415, 2019.

[27] P. Goyal, D. K. Lobiyal and C. P. Katti, "Dynamic User Preference Based Network Selection for Vertical Handoff in Heterogeneous Wireless Networks," *WIRELESS PERSONAL COMMUNICATIONS,* vol. 98, pp. 725-742, 2018.

[28] I. Bisio and A. Sciarrone, "Fast Multiattribute Network Selection Technique for Vertical Handover in Heterogeneous Emergency Communication Systems," *WIRELESS COMMUNICATIONS AND MOBILE COMPUTING,* vol. 2019, pp. 1-17, 2019.

[29] L. M., A. A. and S. A., "An Improved Policy for Network Selection Decision Based on Enhanced-TOPSIS and Utility Function," in *2017 13th International Wireless Communications and Mobile Computing Conference (IWCMC)*, NEW YORK, 2017, pp. 2175-2180.

[30] R. K. Goyal, S. Kaushal and A. K. Sangaiah, "The Utility Based Non-Linear Fuzzy AHP Optimization Model for Network Selection in Heterogeneous Wireless Networks," *APPLIED SOFT COMPUTING,* vol. 67, pp. 800-811, 2018.

[31] K. Ahuja, B. Singh and R. Khanna, "Network Selection Based on Weight Estimation of QoS Parameters in Heterogeneous Wireless Multimedia Networks," *WIRELESS PERSONAL COMMUNICATIONS,* vol. 77, pp. 3027-3040, 2014.

[32] L. G., Y. H., G. X., and Q. Y., "Joint Access Selection and Bandwidth Allocation Algorithm Supporting User Requirements and Preferences in Heterogeneous Wireless Networks," *IEEE ACCESS,* vol. 7, pp. 23914-23929, 2019.

[33] M. Khan, G. Park, W. Cho, G. Seong, and K. Han, "A Handover Management Scheme Based on User-Preferences and Network-Centric Approach," *KSII TRANSACTIONS ON INTERNET AND INFORMATION SYSTEMS,* vol. 9, pp. 344-357, 2015.

Universiti Utara Malaysia

[34] X. Wu and Q. Du, "Utility-Function-Based Radio-Access-Technology Selection for Heterogeneous Wireless Networks," *COMPUTERS AND ELECTRICAL ENGINEERING,* vol. 52, pp. 171-182, 2016.

[35] Y. K. Salih, O. H. See, R. W. Ibrahim, S. Yussof, and A. Iqbal, "A User-Centric Game Selection Model Based on User Preferences for The Selection of The Best Heterogeneous Wireless Network," *ANNALS OF TELECOMMUNICATIONS,* vol. 70, pp. 239-248, 2015.

[36] G. Liang and H. Yu, "Network Selection Algorithm for Heterogeneous Wireless Networks Based on Service Characteristics and User Preferences," *EURASIP Journal on Wireless Communications and Networking,* vol. 2018, pp. 241-257, 2018.

[37] K. Lin, C. Li, D. Tian, A. Ghoneim, M. S. Hossain, and S. U. Amin, "Artificial-Intelligence-Based Data Analytics for Cognitive Communication in Heterogeneous Wireless Networks," *IEEE WIRELESS COMMUNICATIONS,* vol. 26, pp. 83-89, 2019.

[38] J. Wang and W. Cheng, "Heterogeneous Quality of Experience Guarantees Over Wireless Networks," *CHINA COMMUNICATIONS,* vol. 15, pp. 51-59, 2018.

[39] L. B. He, D. D. Jiang and C. Wei, "A QoE-Based Dynamic Energy-Efficient Network Selection Algorithm," *WIRELESS NETWORKS,* vol. 27, pp. 3585-3595, 2021.

[40] Behrouz, Shahgholi, Ghahfarokhi, And, Naser, and Movahhedinia, "A Survey on Applications of IEEE 802.21 Media Independent Handover Framework in Next Generation Wireless Networks," *COMPUTER COMMUNICATIONS,* vol. 36, pp. 1101-1119, 2013.

[41] X. Yan, Y. A. Sekercioglu and S. Narayanan, "A Survey of Vertical Handover Decision Algorithms in Fourth Generation Heterogeneous Wireless Networks," *COMPUTER NETWORKS,* vol. 54, pp. 1848-1863, 2010.

[42] S. Reddy and S. D. Roy, "Inter Radio Access Technology [IRAT] Handover Algorithms for Heterogeneous Wireless Networks," *WIRELESS PERSONAL*

COMMUNICATIONS, vol. 114, pp. 2477-2491, 2020.

[43] Y. Li, B. Cao and C. Wang, "Handover Schemes in Heterogeneous LTE Networks: Challenges and Opportunities," *IEEE WIRELESS COMMUNICATIONS,* vol. 23, pp. 112-117, 2016.

[44] M. F. Tuysuz and R. Trestian, "Energy-Efficient Vertical Handover Parameters, Classification and Solutions over Wireless Heterogeneous Networks: A Comprehensive Survey," *WIRELESS PERSONAL COMMUNICATIONS,* vol. 97, pp. 1155-1184, 2017.

[45] D. Lopez-Perez, I. Guevenc and X. Chu, "Mobility Management Challenges in 3GPP Heterogeneous Networks," *IEEE COMMUNICATIONS MAGAZINE,* vol. 50, pp. 70-78, 2012.

[46] I. Shayea, M. Ergen, M. H. Azmi, S. A. Colak, and Y. I. Daradkeh, "Key Challenges, Drivers and Solutions for Mobility Management in 5G Networks: A Survey," *IEEE ACCESS,* vol. 8, pp. 172534-172552, 2020.

[47] C. Chen, R. A. Berry, M. L. Honig, and V. G. Subramanian, "Pricing, Bandwidth Allocation, and Service Competition in Heterogeneous Wireless Networks," *IEEE-ACM TRANSACTIONS ON NETWORKING,* vol. 28, pp. 2299-2308, 2020-1-1 2020.

[48] A. Zhu, M. Ma, S. Guo, S. Yu, and L. Yi, "Adaptive Multi-Access Algorithm for Multi-Service Edge Users in 5G Ultra-Dense Heterogeneous Networks," *IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY,* vol. PP, pp. 2807-2821, 2021.

[49] N. Quoc-Thinh, N. Agoulmine, E. H. Cherkaoui, and L. Toni, "Multicriteria Optimization of Access Selection to Improve the Quality of Experience in Heterogeneous Wireless Access Networks," *IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY,* vol. 62, pp. 1785-1800, 2013.

[50] A. Monteiro, E. Souto, R. Pazzi, and M. Nogueira, "Context-Aware Network Selection in Heterogeneous Wireless Networks," *COMPUTER COMMUNICATIONS,* vol. 135, pp. 1-15, 2019.

Universiti Utara Malaysia

[51] T. Thumthawatworn, P. Tillapart and P. Santiprabhob, "Adaptive Multi-fuzzy Engines for Handover Decision in Heterogeneous Wireless Networks," *WIRELESS PERSONAL COMMUNICATIONS,* vol. 93, pp. 1005-1026, 2017.

[52] H. W. Yu and B. Zhang, "A Heterogeneous Network Selection Algorithm Based on Network Attribute and User Preference," *AD HOC NETWORKS,* vol. 72, pp. 68-80, 2018.

[53] J. D., H. L., L. Z., S. H., and Q. W., "A Joint Multi-Criteria Utility-Based Network Selection Approach for Vehicle-to-Infrastructure Networking," *IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS,* vol. 19, pp. 3305-3319, 2018.

[54] I. Chamodrakas and D. Martakos, "A Utility-Based Fuzzy TOPSIS Method for Energy Efficient Network Selection in Heterogeneous Wireless Networks," *APPLIED SOFT COMPUTING,* vol. 12, pp. 1929-1938, 2012.

[55] M. Khan, A. Ahmad, S. Khalid, S. H. Ahmed, S. Jabbar, and J. Ahmad, "Fuzzy Based Multi-Criteria Vertical Handover Decision Modeling in Heterogeneous Wireless Networks," *MULTIMEDIA TOOLS AND APPLICATIONS,* vol. 76, pp. 24649-24674, 2017.

[56] W. Chen, S. Gong and X. Jiang, "Fuzzy Multiple Attribute Decision Access Scheme in Heterogeneous Wireless Network," *MULTIMEDIA TOOLS AND APPLICATIONS,* vol. 76, pp. 20049-20065, 2017.

[57] R. Trestian, O. Ormond and G. Muntean, "Performance Evaluation of MADM-Based Methods for Network Selection in A Multimedia Wireless Environment," *WIRELESS NETWORKS,* vol. 21, pp. 1745-1763, 2015.

[58] M. Ma, A. Zhu, S. Guo, X. Wang, B. Liu, and X. Su, "Heterogeneous Network Selection Algorithm for Novel 5G Services Based on Evolutionary Game," *IET COMMUNICATIONS,* vol. 14, pp. 320-330, 2020.

[59] A. Habbal, S. I. Goudar and S. Hassan, "Context-Aware Radio Access Technology Selection in 5G Ultra Dense Networks," *IEEE ACCESS,* vol. 5, pp. 6636-6648, 2017.

Universiti Utara Malaysia

[60] H. W. Yu and B. Zhang, "A Hybrid MADM Algorithm Based on Attribute Weight and Utility Value for Heterogeneous Network Selection," *JOURNAL OF NETWORK AND SYSTEMS MANAGEMENT,* vol. 27, pp. 756-783, 2019.

[61] A. Awad, A. Mohamed and C. Chiasserini, "Dynamic Network Selection in Heterogeneous Wireless Networks A User-Centric Scheme for Improved Delivery," *IEEE CONSUMER ELECTRONICS MAGAZINE,* vol. 6, pp. 53-60, 2017.

[62] A. Ahmed, L. M. Boulahia and D. Gaiti, "Enabling Vertical Handover Decisions in Heterogeneous Wireless Networks: A State-of-the-Art and A Classification," *IEEE COMMUNICATIONS SURVEYS AND TUTORIALS,* vol. 16, pp. 776-811, 2014.

[63] L. Wang and G. G. S. Kuo, "Mathematical Modeling for Network Selection in Heterogeneous Wireless Networks - A Tutorial," *IEEE COMMUNICATIONS SURVEYS AND TUTORIALS,* vol. 15, pp. 271-292, 2013.

[64] S. Fernandes and A. Karmouch, "Vertical Mobility Management Architectures in Wireless Networks: A Comprehensive Survey and Future Directions," *IEEE COMMUNICATIONS SURVEYS AND TUTORIALS,* vol. 14, pp. 45-63, 2012.

[65] R. Ferrus, O. Sallent and R. Agusti, "Interworking in Heterogeneous Wireless Networks: Comprehensive Framework and Future Trends," *IEEE WIRELESS COMMUNICATIONS,* vol. 17, pp. 22-31, 2010.

[66] M. Kassar, B. Kervella and G. Pujolle, "An Overview of Vertical Handover Decision Strategies In Heterogeneous Wireless Networks," *COMPUTER COMMUNICATIONS,* vol. 31, pp. 2607-2620, 2008.

[67] M. Zekri, B. Jouaber and D. Zeghlache, "A Review on Mobility Management and Vertical Handover Solutions Over Heterogeneous Wireless Networks," *COMPUTER COMMUNICATIONS,* vol. 35, pp. 2055-2068, 2012.

[68] H. Lee, D. Kim, B. Chung, and H. Yoon, "Adaptive Hysteresis Using Mobility Correlation for Fast Handover," *IEEE COMMUNICATIONS LETTERS,* vol. 12, pp. 152-154, 2008.

[69] K. Ahuja, B. Singh and R. Khanna, "Network Selection Algorithm Based on Link Quality Parameters for Heterogeneous Wireless Networks," *OPTIK,* vol. 125, pp. 3657-3662, 2014.

[70] K. M. Hosny, M. M. Khashaba, W. I. Khedr, and F. A. Amer, "New Vertical Handover Prediction Schemes for LTE-WLAN Heterogeneous Networks," *PLOS ONE,* vol. 14, p. e0215334, 2019.

[71] H. Yu, L. Chen and J. Yu, "Network Selection Algorithm Based on Chi-Square Distance in Heterogeneous Wireless Networks," *WIRELESS PERSONAL COMMUNICATIONS,* vol. 111, pp. 1625-1643, 2020.

[72] Y. Zhong, H. Wang and H. Lv, "A Cognitive Wireless Networks Access Selection Algorithm Based on MADM," *AD HOC NETWORKS,* vol. 109, p. 102286, 2020.

[73] I. Cinemre and T. Mahmoodi, "Learning-Based Multi Attribute Network Selection in Heterogeneous Wireless Access," *WIRELESS PERSONAL COMMUNICATIONS,* vol. 125, pp. 351-366, 2022.

[74] J. Ma, Z. P. Fan and L. H. Huang, "A Subjective and Objective Integrated Approach to Determine Attribute Weights," *EUROPEAN JOURNAL OF OPERATIONAL RESEARCH,* vol. 112, pp. 397-404, 1999.

[75] E. Obayiuwana and O. E. Falowo, "Network Selection in Heterogeneous Wireless Networks Using Multi-Criteria Decision-Making Algorithms: A Review," *WIRELESS NETWORKS,* vol. 23, pp. 2617-2649, 2017.

[76] L. Tang, S. Ji and J. Yan, "A Heterogeneous Network Access Selection Algorithm Based on Attribute Dependence," *WIRELESS PERSONAL COMMUNICATIONS,* vol. 92, pp. 1163-1176, 2017.

[77] R. Verma and N. P. Singh, "GRA Based Network Selection in Heterogeneous Wireless Networks," *WIRELESS PERSONAL COMMUNICATIONS,* vol. 72, pp. 1437-1452, 2013.

[78] M. Fouladian, F. Hendessi and M. A. Pourmina, "Using AHP and Interval VIKOR Methods to Gateway Selection in Integrated VANET and 3G

Universiti Utara Malaysia

Heterogeneous Wireless Networks in Sparse Situations," *ARABIAN JOURNAL FOR SCIENCE AND ENGINEERING,* vol. 41, pp. 2787-2800, 2016.

[79] A. M. Miyim, M. Ismail and R. Nordin, "Performance Analysis of Multi-level Vertical Handover in Wireless Heterogeneous Networks," *WIRELESS PERSONAL COMMUNICATIONS,* vol. 2019, pp. 1109-1130, 2017.

[80] X. Yan, P. Dong, T. Zheng, and H. Zhang, "Fuzzy and Utility Based Network Selection for Heterogeneous Networks in High-Speed Railway," *WIRELESS COMMUNICATIONS AND MOBILE COMPUTING,* vol. 2017, pp. 1-14, 2017.

[81] L. A. Zadeh, "Fuzzy Sets," *INFORMATION AND CONTROL,* vol. 8, pp. 338-353, 1965.

[82] E. Mamdani, "Applications of Fuzzy Algorithm for Control of a Simple Dynamic Plant," *Proceedings of IEEE,* vol. 121, 1974.

[83] T. T. and S. M., "Fuzzy Identification of Systems and Its Applications to Modeling and Control," *IEEE TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS,* vol. SMC-15, pp. 116-132, 1985.

[84] J. A. de Sarges Cardoso, F. P. Ferreira Da Silva, T. C. de Carvalho, J. J. Henrique Ferreira Junior, N. L. Vijaykumar, and C. R. Lisboa Frances, "Heterogeneous Wireless Networks with Mobile Devices of Multiple Interfaces for Simultaneous Connections Using Fuzzy System," *PLOS ONE,* vol. 16, pp. 1-19, 2021.

[85] B. Naeem, R. Ngah and S. Z. M. Hashim, "Reduction in Ping-Pong Effect in Heterogeneous Networks Using Fuzzy Logic," *SOFT COMPUTING,* vol. 23, pp. 269-283, 2019.

[86] M. Taki, M. Heshmati and Y. Omid, "Fuzzy-Based Optimized QoS-Constrained Resource Allocation in a Heterogeneous Wireless Network," *INTERNATIONAL JOURNAL OF FUZZY SYSTEMS,* vol. 18, pp. 1131-1140, 2016.

[87] A. Ali, L. Abbas, M. Shafiq, A. K. Bashir, M. K. Afzal, H. Bin Liaqat, M. H. Siddiqi, and K. S. Kwak, "Hybrid Fuzzy Logic Scheme for Efficient Channel Utilization in Cognitive Radio Networks," *IEEE ACCESS,* vol. 7, pp. 24463-

24476, 2019.

[88] K. Ahuja, B. Singh and R. Khanna, "Network Selection in Wireless Heterogeneous Environment by C-P-F Hybrid Algorithm," *WIRELESS PERSONAL COMMUNICATIONS,* vol. 98, pp. 2733-2751, 2018.

[89] I. Kustiawan and K. Chi, "Handoff Decision Using a Kalman Filter and Fuzzy Logic in Heterogeneous Wireless Networks," *IEEE COMMUNICATIONS LETTERS,* vol. 19, pp. 2258-2261, 2015.

[90] A. Mehbodniya, F. Kaleem, K. K. Yen, and F. Adachi, "A Fuzzy Extension of VIKOR For Target Network Selection in Heterogeneous Wireless Environments," *PHYSICAL COMMUNICATION,* vol. 7, pp. 145-155, 2013.

[91] Y. K. Salih, O. H. See and R. W. Ibrahim, "An Intelligent Selection Method Based on Game Theory in Heterogeneous Wireless Networks," *TRANSACTIONS ON EMERGING TELECOMMUNICATIONS TECHNOLOGIES,* vol. 27, pp. 1641-1652, 2016.

[92] R. Trestian, O. Ormond and G. Muntean, "Game Theory-Based Network Selection: Solutions and Challenges," *IEEE COMMUNICATIONS SURVEYS AND TUTORIALS,* vol. 14, pp. 1212-1231, 2012.

[93] M. F. Ma, A. Q. Zhu, S. T. Guo, X. Q. Wang, B. Liu, and X. Su, "Heterogeneous Network Selection Algorithm for Novel 5G Services Based on Evolutionary Game," *IET COMMUNICATIONS,* vol. 14, pp. 320-330, 2020.

[94] Y. K. Salih, H. S. Ong, R. W. Ibrahim, S. Yussof, and A. Iqbal, "A Novel Noncooperative Game Competing Model Using Generalized Simple Additive Weighting Method to Perform Network Selection in Heterogeneous Wireless Networks," *INTERNATIONAL JOURNAL OF COMMUNICATION SYSTEMS,* vol. 28, pp. 1112-1125, 2015.

[95] N. C. Luong, T. Nguyen, S. Feng, H. T. Nguyen, and I. K. Dong, "Dynamic Network Service Selection in IRS-assisted Wireless Networks: A Game Theory Approach," *IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY,* vol. 70, pp. 5160-5165, 2021.

Universiti Utara Malaysia

[96] P. Goyal, D. K. Lobiyal and C. P. Katti, "Dynamic User Preference Based Group Vertical Handoffs in Heterogeneous Wireless Networks: A Non-Cooperative Game Approach," *WIRELESS NETWORKS,* vol. 26, pp. 775-789, 2020.

[97] Q. B. Chen, W. G. Zhou, R. Chai, and L. Tang, "Game-Theoretic Approach for Pricing Strategy and Network Selection in Heterogeneous Wireless Networks," *IET COMMUNICATIONS,* vol. 5, pp. 676-682, 2011.

[98] D. Niyato and E. Hossain, "Dynamics of Network Selection in Heterogeneous Wireless Networks: An Evolutionary Game Approach," *IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY,* vol. 58, pp. 2008-2017, 2009.

[99] X. Wang, J. Li, L. Wang, C. Yang, and Z. Han, "Intelligent User-Centric Network Selection: A Model-Driven reinforcement Learning framework," *IEEE ACCESS,* vol. 7, pp. 21645-21661, 2019.

[100] L. Giupponi, R. Agustí, J. Perez-Romero, and O. Sallent, "Fuzzy Neural Control for Economic-Driven Radio Resource Management in Beyond 3G Networks," *IEEE TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS,* vol. 39, pp. 170-189, 2009.

[101] L. G., Y. H., G. X., and Q. Y., "Joint Access Selection and Bandwidth Allocation Algorithm Supporting User Requirements and Preferences in Heterogeneous Wireless Networks," *IEEE ACCESS,* vol. 7, pp. 23914-23929, 2019.

[102] G. Liang, X. Guo, G. Sun, and J. Fang, "A User-Oriented Intelligent Access Selection Algorithm in Heterogeneous Wireless Networks," *COMPUTATIONAL INTELLIGENCE AND NEUROSCIENCE,* vol. 2020, pp. 1-20, 2020.

[103] A. Calhan and C. Ceken, "Artificial Neural Network Based Vertical Handoff Algorithm for Reducing Handoff Latency," *WIRELESS PERSONAL COMMUNICATIONS,* vol. 71, pp. 2399-2415, 2013.

[104] Y. Chen, C. Chang and C. Y. Huang, "Fuzzy Q-Learning Admission Control for WCDMA/WLAN Heterogeneous Networks with Multimedia Traffic," *IEEE TRANSACTIONS ON MOBILE COMPUTING,* vol. 8, pp. 1469-1479, 2009.

Universiti Utara Malaysia

[105]L. Giupponi, R. Agusti, J. Perez-Romero, and O. S. Roig, "A Novel Approach for Joint Radio Resource Management Based on Fuzzy Neural Methodology," *IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY,* vol. 57, pp. 1789-1805, 2008.

[106]X. Chen, Z. Li, K. Wang, and L. Xing, "MDP-Based Network Selection with Reward Optimization in HetNets," *CHINESE JOURNAL OF ELECTRONICS,* vol. 1, pp. 183-190, 2018.

[107]J. L. Xie, W. J. Gao and C. R. Li, "Heterogeneous Network Selection Optimization Algorithm Based on a Markov Decision Model," *CHINA COMMUNICATIONS,* vol. 17, pp. 40-53, 2020.

[108]Q. Kuang, W. Utschick and A. Dotzler, "Optimal Joint User Association and Multi-Pattern Resource Allocation in Heterogeneous Networks," *IEEE TRANSACTIONS ON SIGNAL PROCESSING,* vol. 64, pp. 3388-3401, 2016.

[109]G. Liang, G. Sun, J. Fang, X. Guo, and H. Yu, "An Access Selection Algorithm for Heterogeneous Wireless Networks Based on Optimal Resource Allocation," *WIRELESS COMMUNICATIONS AND MOBILE COMPUTING,* vol. 2020, pp. 1-13, 2020.

[110]B. Mefgouda and H. Idoudi, "New Network Interface Selection Based on MADM and Multi-Objective Whale Optimization Algorithm in Heterogeneous Wireless Networks," *JOURNAL OF SUPERCOMPUTING,* vol. 79, pp. 3580-3615, 2023.

[111]S. Goudarzi, W. H. Hassan, M. H. Anisi, and S. A. Soleymani, "MDP-Based Network Selection Scheme by Genetic Algorithm and Simulated Annealing for Vertical-Handover in Heterogeneous Wireless Networks," *WIRELESS PERSONAL COMMUNICATIONS,* vol. 92, pp. 399-436, 2017.

[112]E. Khloussy, X. Gelabert and Y. Jiang, "Investigation on MDP-Based Radio Access Technology Selection in Heterogeneous Wireless Networks," *COMPUTER NETWORKS,* vol. 91, pp. 57-67, 2015.

[113]E. Stevens-Navarro, Y. Lin and V. Wong, "An MDP-Based Vertical Handoff

Universiti Utara Malaysia

Decision Algorithm for Heterogeneous Wireless Networks," *IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY,* vol. 57, pp. 1243-1254, 2008.

[114]S. Lee, K. Sriram, K. Kim, Y. H. Kim, and N. Golmie, "Vertical Handoff Decision Algorithms for Providing Optimized Performance in Heterogeneous Wireless Networks," *IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY,* vol. 58, pp. 865-881, 2009.

[115]Y. Choi, H. Kim, S. Han, and Y. Han, "Joint Resource Allocation for Parallel Multi-Radio Access in Heterogeneous Wireless Networks," *IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS,* vol. 9, pp. 3324-3329, 2010.

[116]P. Bosch, T. De Schepper, E. Zeljkovic, J. Famaey, and S. Latre, "Orchestration of Heterogeneous Wireless Networks: State of the art and remaining challenges," *COMPUTER COMMUNICATIONS,* vol. 149, pp. 62-77, 2020.

[117]H. Yu, Y. Ma and J. Yu, "Network Selection Algorithm for Multiservice Multimode Terminals in Heterogeneous Wireless Networks," *IEEE ACCESS,* vol. 7, pp. 46240-46260, 2019.

[118]J. B. Ernst, S. C. Kremer and J. J. P. C. Rodrigues, "A Survey of QoS/QoE Mechanisms in Heterogeneous Wireless Networks," *PHYSICAL COMMUNICATION,* vol. 13, pp. 61-72, 2014.

[119]L. B. He, D. D. Jiang and C. Wei, "A QoE-Based Dynamic Energy-Efficient Network Selection Algorithm," *WIRELESS NETWORKS,* vol. 27, pp. 3585-3595, 2021.

[120]T. Abu-Ain, R. Ahmad, R. Wazirali, and W. Abu-Ain, "A New SDN-Handover Framework for QoS in Heterogeneous Wireless Networks," *ARABIAN JOURNAL FOR SCIENCE AND ENGINEERING,* vol. 48, pp. 10857-10873, 2023.

[121]L. Wang, Z. Lu, X. Wen, and W. Guan, "Converged Management in Heterogeneous Wireless Networks Based on Resource Virtualization," *MOBILE*

NETWORKS AND APPLICATIONS, vol. 20, pp. 53-61, 2015.

[122]L. Tian, G. Zhai, L. Huang, Y. Zhou, and J. Shi, "Research on Key Technologies of Heterogeneous Wireless Network Resource Management Based on Centralized Radio Access Network Architecture," *TELECOMMUNICATIONS SCIENCE,* vol. 29, pp. 25-31, 2013.

[123]S. Lirio Castellanos-Lopez, F. A. Cruz-Perez, G. Hernandez-Valdez, and M. E. Rivero-Angeles, "Analysis and Performance Evaluation of Resource Management Mechanisms in Heterogeneous Traffic Cognitive Radio Networks," *EURASIP JOURNAL ON WIRELESS COMMUNICATIONS AND NETWORKING,* vol. 2017, pp. 218-236, 2017.

[124]K. Lin, C. S. Li, J. Rodrigues, P. Pace, and G. Fortino, "Data-Driven Joint Resource Allocation in Large-scale Heterogeneous Wireless Networks," *IEEE NETWORK,* vol. 34, pp. 163-169, 2020.

[125]A. K. Yadav, K. Singh, P. K. Srivastava, S. Mahamad, A. Alghamdi, D. Baleanu, and A. Ahmadian, "ECCANS: Enhanced CRITIC-based Context-Aware Network Selection algorithm for 5G HetNet," *SUSTAINABLE ENERGY TECHNOLOGIES AND ASSESSMENTS,* vol. 60, 2023.

[126]G. H. S. Carvalho, I. Woungang, A. Anpalagan, and E. Hossain, "QoS-Aware Energy-Efficient Joint Radio Resource Management in Multi-RAT Heterogeneous Networks," *IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY,* vol. 65, pp. 6343-6365, 2016.

[127]E. Z. Tragos, G. Tsiropoulos, G. T. Karetsos, and S. A. Kyriazakos, "Admission Control for QoS Support in Heterogeneous 4G Wireless Networks," *IEEE NETWORK,* vol. 22, pp. 30-37, 2008.

[128]E. Mingozzi, G. Stea, M. A. Callejo-Rodriguez, J. Enriquez-Gabeiras, G. Garcia-de-Blas, F. J. Ramon-Salquero, W. Burakowski, A. Beben, J. Sliwinski, H. Tarasiuk, O. Dugeon, M. Diaz, L. Baresse, and E. Monteiro, "EuQoS: End-to-End Quality of Service over Heterogeneous Networks," *COMPUTER COMMUNICATIONS,* vol. 32, pp. 1355-1370, 2009.

Universiti Utara Malaysia

[129]L. T. M. Blessing and A. Chakrabarti, *DRM, a Design Research Methodology*: Springer, 2009.

[130]A. Habbal, "TCP SINTOK: Transmission Control Protocol with Delay-based Loss Detection and Contention Avoidance Mechanisms for Mobile Adhoc Networks,": Ph.D. dissertation, School of Computing, Universiti Utara Malaysia, 2014.

[131]I. G. Swetha, "Context-aware Multi-attribute Decision Making for Radio Access Technology Selection in Ultra Dense Network,": Ph.D. dissertation, School of Computing, Universiti Utara Malaysia, 2017.

[132]G. S. R., "Verification, Validation and Accreditation of Simulation Models," in *2000 Winter Simulation Conference Proceedings*, 2000, pp. 50-59 vol.1.

[133]L. R. M., K. E., P. M. S., and C. U., "Wireless Sensor Network Simulation Frameworks: A Tutorial Review: MATLAB/Simulink Bests the Rest," *IEEE CONSUMER ELECTRONICS MAGAZINE,* vol. 5, pp. 63-69, 2016.

[134]L. S. D. F. N., "Tools and Techniques for the Performance Evaluation of Communication Networks," *IEEE COMMUNICATIONS MAGAZINE,* vol. 36, pp. 32-34, 1998.

[135]X. Guoqiang, F. W. J., L. Tho, and T. S., "An Analytical Model for Performance Evaluation of Parallel Interference Cancellers in CDMA Systems," *IEEE COMMUNICATIONS LETTERS,* vol. 4, pp. 184-186, 2000.

[136]B. R. Chandavarkar, "Media Independent Handover and Mobile IPv6-Based UDP Performance Evaluation Suite for Heterogeneous Wireless Networks," *WIRELESS PERSONAL COMMUNICATIONS,* vol. 129, pp. 1197-1228, 2023.

[137]W. H., I. L. D. and H. J., "A General Performance Evaluation Framework for Network Selection Strategies in 3G-WLAN Interworking Networks," *IEEE TRANSACTIONS ON MOBILE COMPUTING,* vol. 12, pp. 868-884, 2013.

[138]J. Ali, R. W. Ahmad, T. Maqsood, J. Rodrigues, N. Haq, S. Sarwar, T. Iqbal, and S. A. Madani, "Network Selection in Heterogeneous Access Networks

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Simultaneously Satisfying User Profile and QoS," *INTERNATIONAL JOURNAL OF COMMUNICATION SYSTEMS,* vol. 31, pp. 3730-3746, 2018.

[139]Y. K. Salih, O. H. See, R. W. Ibrahim, S. Yussof, and A. Iqbal, "An Overview of Intelligent Selection and Prediction Method in Heterogeneous Wireless Networks," *JOURNAL OF CENTRAL SOUTH UNIVERSITY,* vol. 21, pp. 3138-3154, 2014.

[140]W. Ho and X. Ma, "The State-of-the-art Integrations and Applications of The Analytic Hierarchy Process," *EUROPEAN JOURNAL OF OPERATIONAL RESEARCH,* vol. 267, pp. 399-414, 2018.

[141]S. Kubler, J. Robert, W. Derigent, A. Voisin, and Y. Le Traon, "A State-of-the-Art Survey & Testbed of Fuzzy AHP (FAHP) Applications," *EXPERT SYSTEMS WITH APPLICATIONS,* vol. 65, pp. 398-422, 2016.

[142]Q. Gu and Z. Xuan, "A New Approach for Ranking Fuzzy Numbers Based on Possibility Theory," *JOURNAL OF COMPUTATIONAL AND APPLIED MATHEMATICS,* vol. 309, pp. 674-682, 2017.

[143]S. S. Zhao, F. Wang, Y. Q. Ning, Y. Xiao, and D. Y. Zhang, "Vertical Handoff Decision Algorithm combined Improved Entropy Weighting with GRA for Heterogeneous Wireless Networks," *KSII TRANSACTIONS ON INTERNET AND INFORMATION SYSTEMS,* vol. 14, pp. 4611-4624, 2020.

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