DOCTORAL THESIS

Management and Selection of Radio Access Technologies in 5G Wireless Networks: Implementation and Performance Evaluation of an Integrated Fuzzy-based System and a Testbed

Author:
Phudit AMPRIRIT

Adviser:
Prof. Leonard BAROLLI

INA LABORATORY
GRADUATE SCHOOL OF ENGINEERING
FUKUOKA INSTITUTE OF TECHNOLOGY

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Abstract

The emergence of Fifth Generation (5G) wireless networks brings a paradigm shift towards providing dense network services and a diverse array of network configurations tailored to meet user requirements. Leveraging the capabilities of Software-Defined Networking (SDN) coupled with Network Slicing (NS) presents a promising approach for efficient resource allocation and traffic management. However, the deployment of 5G wireless networks is accompanied by many challenges such as the enhancement of spectrum efficiency to accommodate increasing demands of wireless data services and the improvement of network capacity and throughput to accommodate the exponential growth of connected devices and data traffic.

To deal with these challenges, this research work proposes an integrated system for management and selection of Radio Access Technologies (RATs) in 5G wireless networks considering Fuzzy Logic (FL) and SDN approaches. We call this system: Integrated System for Resource and Traffic Management (ISRTM) in 5G wireless networks. The proposed system is composed of three modules called Fuzzy-based RATs Selection Module (FRSM), Fuzzy-based Admission Control Module (FACM) and Fuzzy-based Handover Module (FHM). The FRSM selects RAT in 5G wireless networks in order that a user to connect with an appropriate RAT for efficient and reliable communication. The FACM deals with Call Admission Control (CAC), which decides whether to accept or reject a connection request from a new user. The FHM deal with handover procedure, which considers not only different base stations or access technologies but also different slices.

We implement different modules and for each module we consider different parameters. We compare the performance of the implemented modules in order to understand how each parameter influences the decision-making process and identify the most effective system configuration for optimal performance. We evaluated the proposed system by simulations. The simulation results show that proposed system has a good behavior. Furthermore, the performance of the proposed system correlates with the number of parameters under consideration and the associated complexity. We also designed and implemented a testbed in order to compare the simulation results with experimental results. The performance evaluation shows that the trend of simulation results and experimental results is the same. Also, the simulation and experimental data are very close.

The contributions of this thesis are as follows. 1) Proposal of Integrated System for Resource and Traffic Management (ISRTM). 2) Implementation of three modules: FRSM, FHM and FACM. 3) Comparison of simulation results for different fuzzy-based systems. 4) Testbed implementation for FRSM. 5) Comparison of simulation results with experimental results.

The thesis structure is as follows. Chapter 1 introduces the background, motivation, contribution and structure of this thesis. Chapter 2 presents wireless networks. The 5G Wireless Networks are described in Chapter 3. In Chapter 4, we present SDN, where we explain the structure of SDN and its advantages and disadvantages. In Chapter 5 are discussed admission control, handover and RATs. In Chapter 6 are introduced Intelligent Algorithms such as Genetic Algorithm (GA), Neural Networks (NNs) and Particle Swarm Optimization (PSO). In Chapter 7, we explain the FL. In Chapter 8 are presented the proposed systems, where we describe in detail the input and output parameters. In Chapter 9 are shown the simulation results for different input parameters and experiment results using the testbed. Finally, the concluding remarks and the future are given in Chapter 10.

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Chapter 1

Introduction

This chapter presents background, motivation and objectives, contributions and organization of thesis.

1.1 Background

The growth of wireless technologies and user's demand of services are increasing rapidly, there will be billions of new devices with unpredictable traffic patterns which provide high data rates. With the appearance of Internet of Things (IoT), these devices will generate Big Data to the Internet, which will cause network congestion and deteriorate the Quality of Service (QoS). Therefore, the Fifth Generation (5G) network is expected to be good and flexible to satisfy user requirements [1]–[4].

The deployment of 5G faces several challenges. Infrastructure costs are significant, including small cells and base stations. Spectrum allocation complexities and regulatory hurdles can delay rollout. Security concerns such as data breaches and cyberattacks pose risks. Interoperability among devices and networks is crucial but challenging due to diverse implementations. Moreover, the digital divide may worsen, with rural and underserved areas facing limited access to 5G, exacerbating inequalities in connectivity. Addressing these issues is vital for realizing the full potential of 5G technology.

The 5G is developing by considering three different usage scenarios which have been identified as enhanced mobile broadband (eMBB), ultra-reliable & low latency communications (URLLC) and massive machine type communication (mMTC) [5]–[7]. The eMBB is related to human-essential and has enhanced access to multi-media content and services by increasing seamless Quality of Experience (QoE). The URLLC can improve the latency and reliability. The mMTC can support massive connected devices with long battery lifetime.

For improving the performance of 5G Radio Access Technologies (RATs), multiple base stations (BSs) use heterogeneous RATs (such as GSM, HSPA, LTE, LTE-A, Wi-Fi, and so on) which provide different radio coverages (such as macrocell, microcell, picocell, femtocell, Wi-Fi, etc.) with different transmission power levels in order to provide the mobile users with the best Quality of Experience (QoE), Energy Efficiency (EE), redundancy and reliability [8], [9].

Compared to the 4G, the 5G, network is expect to be better than 4G. In Fig. 1.1 are shown the key challenges of 5G, which are improved spectrum efficiency, reduced latency, low consumption, high data rate, capacity and throughput improvement. For example, the peak data for 5G is expected to be beyond 20 Gbps [10]. In addition, the 5G network will provide users with new experiences such as Ultra High Definition Television (UHDT) on Internet [11] and support a lot of IoT devices with long battery life and high data rates on hotspot areas with high user density[12].

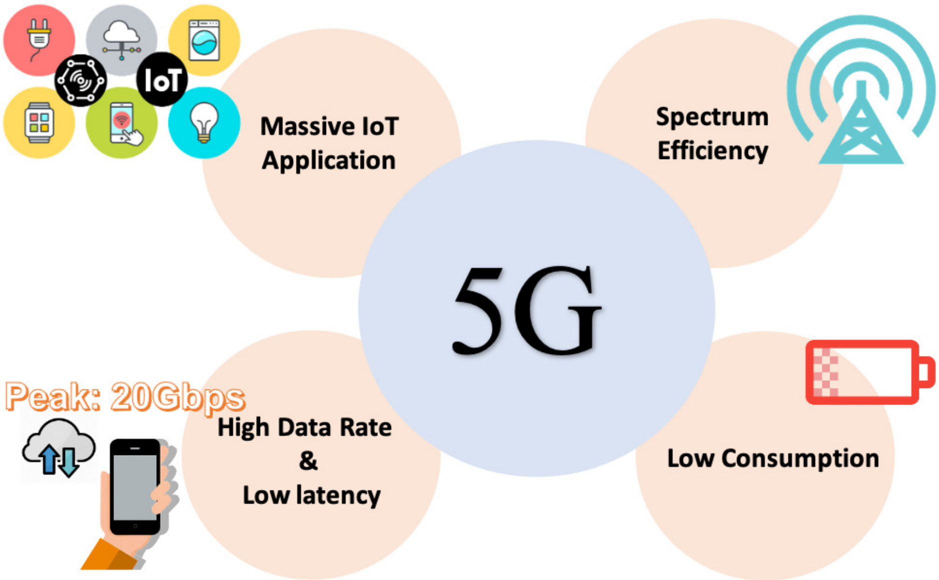


FIGURE 1.1: The key challenges of 5G.

In order to meet new network challenges and because traditional IP networks are complex and very hard to manage, network administrators have to identify and create new methodologies to enhance the network performance for the new era and Software Defined Networking (SDN) is one of them. The SDN is a new networking paradigm that decouples the data plane from control plane in the network and promotes (logical) centralization of network control that have ability to program the network. Thus, the SDN can enhance system management efficiency and processing performance [13]. As an example, the mobile handover mechanism with SDN can be used for reducing the delay in handover processing and improve the QoS [14]–[17].

The Network Slicing (NS) is a new technology that uses SDN and Network Function Virtualization (NFV) for new services over the same physical network [18]. A slice is a set of network resources which is selected in order to satisfy the requirements of the services. It can provide on-demand customized reliable service in network with limited resource by slicing a physical network into several logical networks. The traffic requirement can be satisfied by different slices with different priority value. Users in the 5G system will get higher QoS than 4G system [18]–[21].

1.2 Motivation and Objectives

The 5G network will accommodate billions of new devices, each bringing its own unpredictable traffic dynamics and a thirst for high data rates. With the appearance of the Internet of Things (IoT), these devices are set to channel immense volumes of Big Data into the Internet, which could inadvertently result in congestion and diminish the overall QoS.

To deal with these issues, in this research, we propose an integrated system considering FL and SDN approaches. We call this system: Integrated System for Resource and Traffic Management (ISRTM) in 5G wireless networks. The proposed system is composed of three modules. We consider various input parameters to discern their impact on the acceptance decisions made by our fuzzy-based system. By comparing different modules, each with their own set of input parameters, we aim to thoroughly evaluate and benchmark their performance. This comparative analysis is crucial in understanding how each parameter influences the decision-making process and in identifying the most effective system configuration for optimal performance.

Three modules are called Fuzzy-based RATs Selection Module (FRSM), Fuzzy-based Admission Control Module (FACM) and Fuzzy-based Handover Module (FHM). FRSM selects RAT in 5G wireless networks, so that a user will connect with an appropriate RAT in order to have efficient and reliable communication. FACM deals with Call Admission Control (CAC), which decides whether to accept or reject a connection request from a new user. FHM considers Handover in 5G wireless networks which introduces new and complex challenges, because a user does not handover to different base stations or access technologies but also different slices. The constraints on NS should be considered when making a handover decision for satisfying user requirements.

1.3 Thesis Contribution

This thesis contributes to research fields as follows.

- Proposal of Integrated System for Resource and Traffic Management (ISRTM).
- Implementation of three FL-based modules: FRSM, FHM and FACM for RAT selection, handover and call admission control.

- Comparison of simulation results for different FL-based modules.
- Testbed implementation.
- Comparison of simulation results with experimental results.

1.4 Thesis Organization

This thesis consists of ten chapters. The thesis structure is shown in Fig. 1.2. Chapter 1 introduces the background, goal, structure and contribution of this thesis. Chapter 2 presents wireless networks. The 5G Wireless Networks is described in Chapter 3. In Chapter 4, we present SDN. We explain about the structure of SDN and the advantages and disadvantages of SDN in 5G wireless networks. In Chapter 5 are discussed admission control , handover and RATs. In Chapter 6 are introduced Intelligent Algorithms such as Genetic Algorithm (GA), Neural Networks (NNs) and Particle Swarm Optimization (PSO). In Chapter 7, we explain about FL. In Chapter 8 is presented the proposed system. We describe in details the input parameters and output parameter for each module. Chapter 9 shows simulation results for different input parameters and experiment results. Finally, the concluding remarks and the future work are given in Chapter 10.

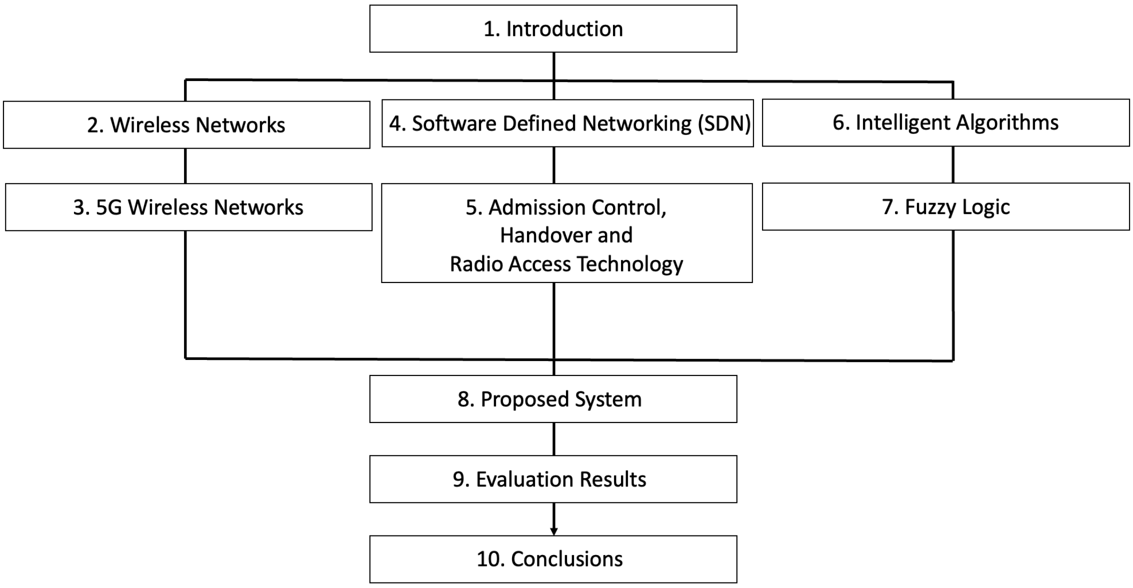


FIGURE 1.2: Thesis structure.

Chapter 2

Wireless Networks

This chapter provides an overview of wireless networks, covering their classification, evolution in mobile telecommunication systems, role in smart city development, and associated security and privacy challenges. Wireless networks are categorized based on coverage area and network topology, with advancements leading to faster data rates and improved connectivity from 1G to 5G mobile networks.

2.1 Classification of Wireless Networks

Wireless networks are classified by communication distance. The classification of various wireless networks is shown in Fig. 2.1.

- **Wireless Personal Area Network (Wireless PAN):** covers a range of about 10 to 20 meters such as Bluetooth, ZigBee, NFC.
- **Wireless Local Area Network (Wireless LAN):** covers a range of about 100 meters such as the 802.11 standards (Wi-Fi standard).
- **Wireless Metropolitan Area Network (Wireless MAN):** is a network that fills the gap between LANs and WANs. It covers several kilometers such as IEEE 802.15 (WiMAX standard).
- **Wireless Regional Area Networks (Wireless RAN):** covers smaller than wireless WAN but wider than wireless MAN such as IEEE802.22 standard.
- **Wireless Wide Area Networks (Wireless WAN):** covers a broad geographical area such as a mobile phone network (UMTS, LTE, etc.).

Wired and wireless networks differ in several key aspects:

- **Space Requirement:** Wireless networks require less physical space compared to wired networks, allowing for closer placement of wireless devices.

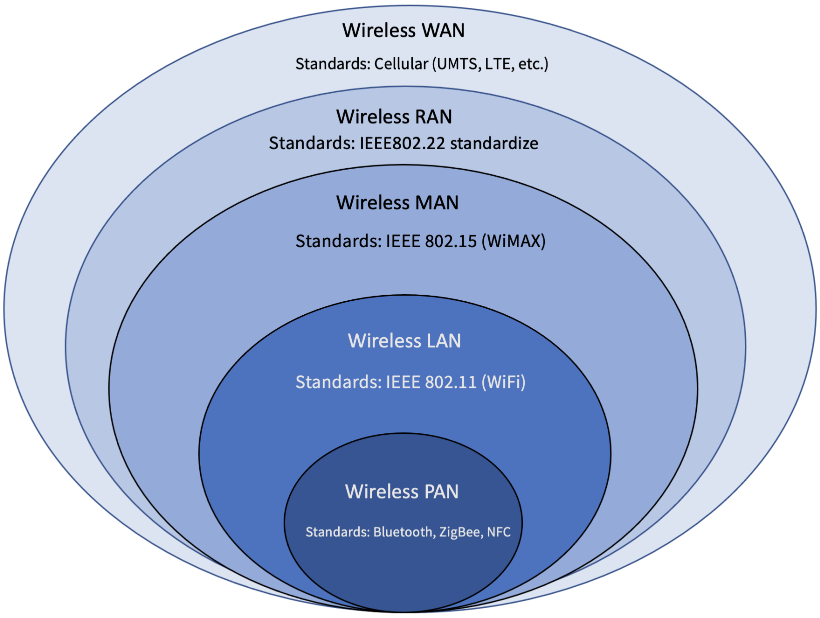


FIGURE 2.1: Classification of various wireless networks.

- **Transmission Medium:** Wired networks utilize electrical currents for data transmission, while wireless networks operate using radio waves. Radio waves can travel greater distances than electricity, making wireless networks advantageous for reaching distant locations.

- **Data Transfer Speed:** Wireless networks typically offer faster data transfer rates compared to wired networks. The use of radio waves enables higher data transmission speeds in wireless networks.

- **Security:** Wired networks establish direct connections between hardware devices, potentially exposing the entire network if one connection is compromised. In contrast, wireless networks employ encryption to protect each connection, making it more challenging for hackers to intercept messages.

- **Cost:** Wired networks require costly cabling infrastructure, whereas wireless networks eliminate the need for wiring altogether. Additionally, wireless networks do not necessitate specialized equipment beyond a wireless router, reducing overall deployment costs.

In next-generation wireless networks, the network infrastructure needs to be efficient, flexible and should provide various vital services such as enhanced mobile broadband, ultra-reliable and low-latency communications, and massive machine-type communications. It should support coexistent accesses of multiple standards and coordinate a heterogeneous network with different types of wireless networks. For example, the 5G, Long-Term Evolution (LTE) and Wi-Fi can be coordinated [22].

2.2 Evolution of Mobile Telecommunication Systems

2.2.1 From 1G to 4G

The First Generation (1G) Systems

The first mobile telecommunication systems were introduced in the early 1980s. The well-known systems are Nordic Mobile Telephony (NMT), which started up in the Nordic countries, Advanced Mobile Phone System (AMPS) in the USA, Total Access Communication System (TACS) in Europe, and J-TACS in Japan.

These communication systems used analog techniques. The signal coverage area was divided into small sectors, each called a cell. The technology came to be called cellular technology, while the phones were called cell phones. When compared with other generations, it has weak points as the individual cell coverage was big and its capacity was small because it couldn't use the available radio spectrum efficiently.

1G networks, which utilized analog signals for communication, faced several significant limitations:

- **Susceptibility to Interference and Eavesdropping:** The use of analog signals made 1G networks prone to interference from other electronic devices, and the lack of robust encryption methods made them vulnerable to eavesdropping. This compromised the security and reliability of communications.

- **Low Capacity:** 1G networks had a limited capacity, constraining the number of users that could be connected simultaneously. During peak usage times, this often resulted in network congestion and degraded call quality.

- **Voice Only Functionality:** The primary function of 1G networks was to support voice calls. They offered limited or no support for other data services like text messaging or internet access, which significantly restricted the functionality of mobile devices.

- **Limited Coverage:** Coverage for 1G networks was generally restricted to urban areas, with rural or remote areas often lacking service. This limited connectivity made it challenging for users to maintain communication while traveling outside of densely populated regions.

- **Roaming Challenges:** Roaming between different 1G networks was fraught with difficulties due to the lack of standardized protocols for network interconnection. This often resulted in connectivity issues for users traveling between areas covered by different carriers.

- **Poor Battery Life:** The mobile phones that operated on 1G networks typically suffered from poor battery life. The analog technologies used were energy-intensive, which meant that devices frequently needed recharging, limiting their practicality for extended use.

The Second Generation (2G) Systems

The Second Generation (2G) systems were introduced in the early 1990s. Compared with previous generation, these systems used digital technology which gave a more efficient use of the radio spectrum and supported instant messaging called the Short Message Service (SMS). Moreover, devices were cheaper and smaller than the 1G systems. The Global System for Mobile Communication (GSM) was the most popular system and designed as a pan-European technology.

The limitation of 2G networks are shown in following.

- **Low transfer rates:** The 2G networks are primarily designed to offer voice services to the subscribers. Thus the transfer rates offered by these networks are low. Though the rates vary across technologies, the average rate is of the order of tens of kilobits per second.

- **Low efficiency for packet switched services:** There is a demand for Internet access, not just at home or the office but also while roaming. Wireless Internet access with the 2G networks is not efficiently implemented.

- **Multiple standards:** With a multitude of competing standards in place, a user can roam in only those networks that support the same standard. This allows the user only limited roaming. Therefore the 2G network technology was semi-global in this respect.

The Third Generation (3G) Systems

The Third Generation (3G) systems came out in the years after 2000. They used different techniques for radio transmission, which can increase the peak data rates and multimedia connectivity to subscribers. The International Telecommunication Union (ITU) under the initiative IMT-2000 has defined 3G systems as capable of supporting high-speed data ranges of 144 kbps to greater than 2 Mbps. A few technologies are able to fulfill the International Mobile Telecommunications (IMT) standards, such as CDMA, UMTS and some variation of GSM such as EDGE. Especially, the Universal Mobile Telecommunication System (UMTS) was the world's dominant system and developed from GSM by changing the technology used on the air interface without changing the core network.

The UMTS air interface has been separated into two implementations.

- **WCDMA (Wideband code division multiple access)** was the most used in the world. It divided the base station and mobile transmissions by means of Frequency Division Duplex (FDD) and deployed a wide bandwidth in 5MHz.
- **TD-SCDMA (Time division synchronous code division multiple access)** was developed in China and deployed by China 3G operator. It uses Time Division Duplex (TDD) and deployed a small bandwidth in 1.6 MHz.

A UMTS network consists of three domains: User Equipment (UE), UMTS Terrestrial Radio Access Network (UTRAN) and Core Network (CN). The UE is the mobile phone combined with SIM (Subscriber Identity Module) card and is called USIM (Universal SIM). USIM has member specific data and can enable the authenticated entry of the subscriber into the network. Figure 2.2 shows the overall UMTS architecture. The UE can perform operations in three modes as Circuit Switched (CS) mode, Packet Switched (PS) mode and CS/PS mode.

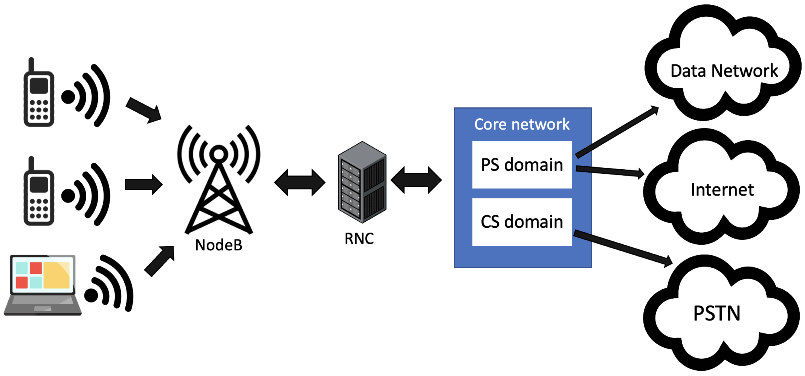


FIGURE 2.2: The UMTS architecture.

In the PS mode, the UE is connected only to the PS domain. In the CS mode the UE is connected only to the core network but the CS/PS mode can make the mobile is working simultaneously to offer both CS and PS services.

The limitation of 3G networks are shown in following.

- **Speed:** Although 3G networks offered faster data speeds compared to 2G networks, they were still slower than later generations like 4G LTE. This limited the performance of data-intensive applications such as HD video streaming and high-quality online gaming.
- **Coverage and Signal Quality:** While 3G networks expanded coverage compared to earlier generations, there were still areas with limited or no coverage, especially in remote or rural areas. Additionally, signal quality could be inconsistent, leading to dropped calls or slow data speeds in certain locations.
- **Capacity:** As mobile data usage continued to grow, 3G networks struggled to keep up with the increasing demand for data services. This sometimes resulted

in network congestion during peak usage times, leading to slower data speeds and degraded service quality for users.

- **Battery Life:** Using 3G networks for data-intensive applications such as internet browsing or video streaming could drain the battery of mobile devices quickly. This was due to the energy-intensive nature of maintaining a 3G connection and transmitting data over the network.

- **High Cost:** In some regions, the cost of accessing 3G networks and using data services was relatively high compared to 2G networks. This limited access to mobile internet services for users with limited financial means and hindered the adoption of 3G technology in certain markets.

- **Technology Obsolescence:** As newer generations of mobile networks were deployed, 3G networks became increasingly outdated. This led to reduced investment in maintaining and expanding 3G infrastructure, eventually resulting in the phase-out of 3G networks in favor of newer technologies.

The Fourth Generation (4G) Systems

The 2G and 3G networks became too congested in the years around 2010. Therefore, a bigger network capacity was needed. The 3GPP began a study into the long term evolution of UMTS in 2004. The aim was that mobile communication systems to deliver data by high data rates and low latencies considering user′s requirements. Figure 2.3 shows the evolution of the system architecture from 2G/3G (GSM/UMTS) to 4G (LTE). In LTE architecture, the Evolved Packet Core (EPC) replaced the packet switched domain of UMTS and GSM. Compared with tradition technologies that only used the packet switching (PS) technologies for data, LTE system distributes all types of information to the user by using PS technologies. The EPC′s radio communications with the mobile is a direct replacement for the UTRAN. The mobile is still known as the User Equipment (UE) but its internal operation is very different from before.

Figure 2.4 shows the EPC is connecting with E-UTRAN and Server PDNs. The main components of EPC have four components as follow.

- **The Home Subscriber Server (HSS)** is a central database that consists of information about all network operator′s subscribers.

- **The Packet Data Network (PDN) Gateway (P-GW)** makes EPC to contact the outside world through the SGI interface.

- **The Serving Gateway (S-GW)** acts like router and forward data between the base station and the P-GW.

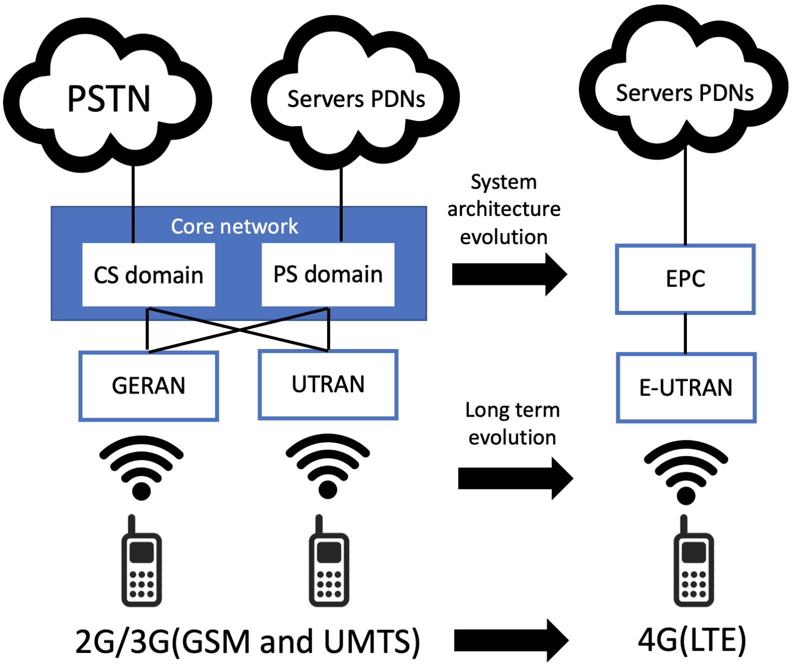


FIGURE 2.3: Evolution of the architecture from 2G/3G to 4G.

- **The Mobility Management Entity (MME)** manages the high-level operation of the mobile by sending signaling messages about security and the management of data stream.

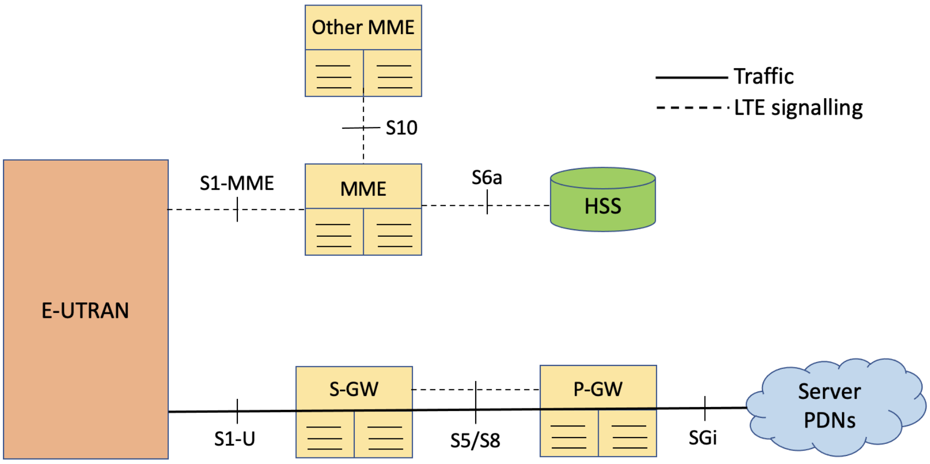


FIGURE 2.4: EPC in the 4G wireless networks.

The limitation of 4G networks is the potential for coverage gaps, particularly in rural or remote areas, due to the cost and complexity of deploying infrastructure. Additionally, network congestion during peak usage times or in densely populated areas can lead to slower data speeds and degraded performance for users.

- **Network Congestion:** During peak usage times or in densely populated areas, 4G networks can experience congestion, leading to slower data speeds and degraded performance for users. This can impact the user experience, especially in crowded urban areas or at large events.

- **Battery Drain:** Utilizing 4G networks for data-intensive applications like streaming video or online gaming can drain the battery of mobile devices quickly. Maintaining a high-speed connection and transmitting large amounts of data requires significant energy consumption.
- **Interference and Signal Attenuation:** 4G signals can be susceptible to interference from physical obstacles like buildings, trees, or terrain, as well as electronic interference from other devices. This can lead to signal attenuation and reduced network performance, particularly indoors or in areas with challenging terrain.
- **Coverage Gaps:** Despite extensive deployment, 4G coverage may still have gaps in rural or remote areas. The infrastructure required for widespread coverage can be costly to implement, leading to slower expansion in certain regions.
- **Limited IoT Support:** While 4G networks can support certain IoT (Internet of Things) devices and applications, they may not be optimized for the massive connectivity and low-latency requirements of certain IoT use cases. This limitation may be addressed by newer generations of mobile networks like 5G, which are designed to better accommodate IoT devices and applications.

The limitation of 4G networks are shown infollowing.

The transformation form 3G/4G to 5G will be challenging because of creating demand requiring new approaches for connectivity, bandwidth and network structure [3], [23]–[25]. The detail of 5G wireless network will be explained in Charter 3.

2.3 Role of Wireless Networks in Smart City Development

The role of wireless networks in smart city development is pivotal. These technologies provide the backbone for connectivity and data exchange, enabling urban areas to be more efficient, sustainable, and livable. Smart cities leverage many IoT devices, sensors, and applications, relying on robust wireless communication networks to collect, transmit, and process data in real-time [26].

In Fig. 2.5, Smart city have six main dimensions as smart economy, smart mobility, smart environment, smart people, smart living and smart governance, which make the number of connected devices rapidly increasing, including IoT devices that cause the increasing demands of applications [27]–[30].

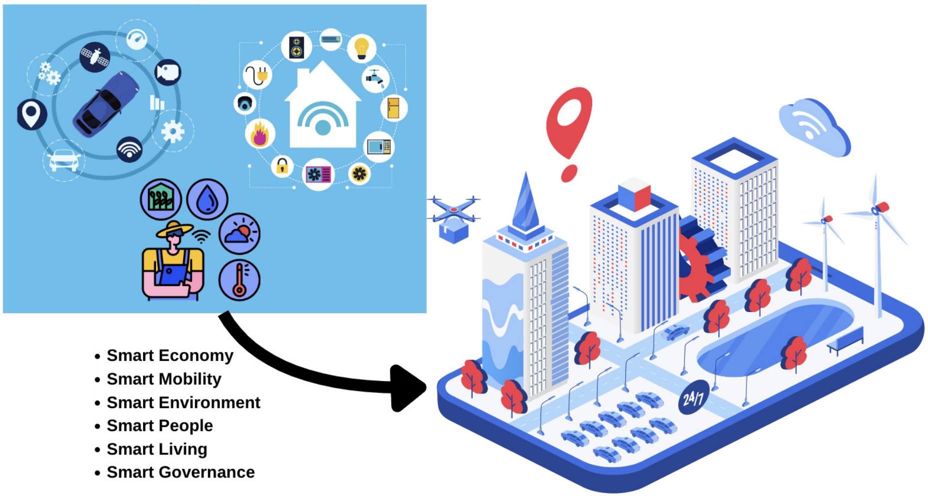


FIGURE 2.5: The six main dimensions of Smart City.

Wireless networks serve as the fundamental connectivity infrastructure for many IoT devices deployed throughout a smart city. These devices, from sensors monitoring air quality to smart meters measuring utility usage, depend on wireless networks for real-time data transmission. Such connectivity empowers city officials and planners to make informed decisions grounded in precise and up-to-date data. By enabling 5G technology, such as SDN, NS, Machine-to-Machine (M2M) communications, massive MIMO and millimeter-wave (mmWave) technologies, IoT networks can improve the performance and reliability of connected IoT devices. Also, 5G-IoT deployment will generate a diverse form of traffic, reliability, bit rates, energy consumption, security and privacy for improving QoS requirements and achieving mmMTC.

Many research works deal with design of systems appropriate for 5G-IoT networks. One example is the utilization of NS for managing a large number of heterogeneous IoT network slices dynamically [31]. Also, 5G-IoT infrastructure implement SDN/NFV for improving load balancing, fault tolerance and congestion avoidance in IoT network [32]. In addition, massive communication interfaces issues (redundant communication capability problem and waste energy) can be improved by 5G massive MIMO [33].

2.4 Security and Privacy Challenges in Wireless Networks

Security and privacy challenges in wireless networks are multifaceted and pervasive, stemming from the inherent vulnerabilities of the wireless communication medium. Eavesdropping, man-in-the-middle attacks, denial of service, spoofing, wireless network sniffing, weak encryption, physical security risks, unauthorized access points, IoT device vulnerabilities, and insider threats all contribute to the complexity of securing wireless networks [34].

In the past, security in telecommunication networks primarily focused on ensuring the proper functionality of billing systems and securing the radio interface by encrypting communication data. In 3G networks, two-way authentication was employed to prevent connection establishment with fake Base Stations (BS). With the advent of 4G networks, advanced cryptographic protocols were introduced for user authentication, along with protection against physical attacks such as tampering of base stations, even those installed in public and user premises. Furthermore, some privacy concerns were addressed to some extent in pre-5G networks, as user data were stored in mobile operators' databases. However, the security and privacy challenges of 5G are surpassing these mechanisms due to architectural changes and the introduction of new services [35].

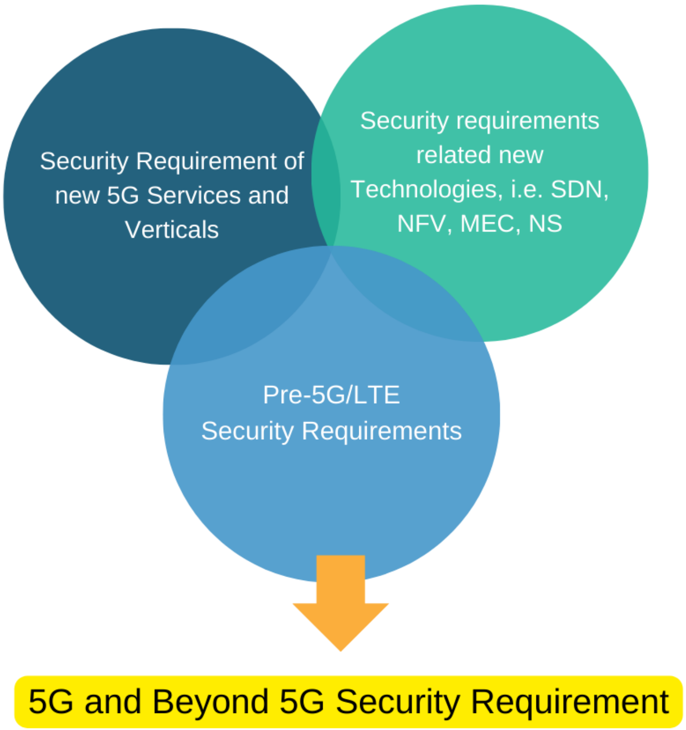


FIGURE 2.6: Security requirements for 5G and beyond 5G.

The security of 5G and beyond 5G networks comprises three main components as shown in Fig. 2.6. Firstly, most security threats and requirements from previous mobile generations remain relevant in 5G and beyond. Secondly, 5G introduces a new set of security challenges due to factors such as increased user numbers, diverse connected devices, novel network services, heightened user privacy concerns, and the emergence of new stakeholders, alongside the necessity to support IoT and mission-critical applications. Lastly, the adoption of network softwarization and the integration of new technologies like SDN, NFV, MEC, and NS bring forth a fresh set of security and privacy challenges.

For Internet of Things (IoT) recently, it has garnered significant attention owing to its appealing and distinctive features. The concept revolves around creating a smart world by integrating millions of intelligent computing devices. Various smart application services have emerged, encompassing domains such as Social IoT (SIoT), Industrial IoT (IIoT), IoT-fog, IoT smart water systems, healthcare IoT, and smart grids [36]. These diverse applications aim to leverage the capabilities of IoT technology to enhance efficiency, productivity, and quality of life across numerous sectors and industries.

In response to the identified threats across various domains of IoT, numerous researchers have proposed solutions to mitigate these security risks. However, addressing security issues in IoT networks poses significant challenges due to these environments' high density and low latency requirements. Many researchers have made notable progress in this area. For example, [37] analyzed security threats and detection schemes in industrial IoT networks, employing statistical, dynamic, and hybrid detection methods. This analysis offers valuable insights for application designers seeking to bolster the security of their systems. Similarly, [38] delves into threat analysis specifically within the context of Public Lighting Systems (PLS) and industrial IoT environments. Additionally, [39] proposes the adoption of abundant Physical Layer security (PHY-Sec) technologies to enhance security in industrial wireless systems, providing valuable guidance for improving overall system security. These efforts underscore the importance of continuous research and innovation in addressing the evolving security challenges posed by IoT networks across various domains.

Addressing security and privacy challenges in wireless networks is critical to safeguarding data transmitted across these systems' integrity, availability, and confidentiality. The inherent vulnerabilities of wireless communication require robust security measures, comprehensive privacy protocols, and vigilant monitoring to prevent unauthorized access and data breaches. Key strategies include employing strong encryption, implementing secure authentication methods, and continuously updating and patching network systems to defend against emerging threats. Additionally, educating end-users about potential security risks and best practices is vital for reinforcing network defenses. As wireless technology continues to evolve and integrate into every aspect of daily life, the emphasis on developing advanced security solutions to combat these challenges becomes increasingly paramount.

Chapter 3

5G Wireless Networks

5G technology represents a significant advancement with its promise of faster data speeds, lower latency, and the capacity to support a vast array of connected devices through the IoT. The 5G is going to be open, more flexible and more easily to be improved than other system. Its importance is underscored by its potential to revolutionize industries such as communication, healthcare, transportation, and manufacturing.

3.1 5G Network Architecture

The 5G cellular architecture is a heterogeneous system that includes macrocells, microcells, small cells, and relays. The 5G networks will have thousands of small cells to meet the latency and throughput requirement. Small cell is closer to the user will reduce latency and increase overall network efficiency by creating subnetworks in 5G wireless network. These subnetworks have the functionality to route data traffic locally for the local users who are communicating with each other while sending the signaling to the main network, as shown in Fig. 3.1.

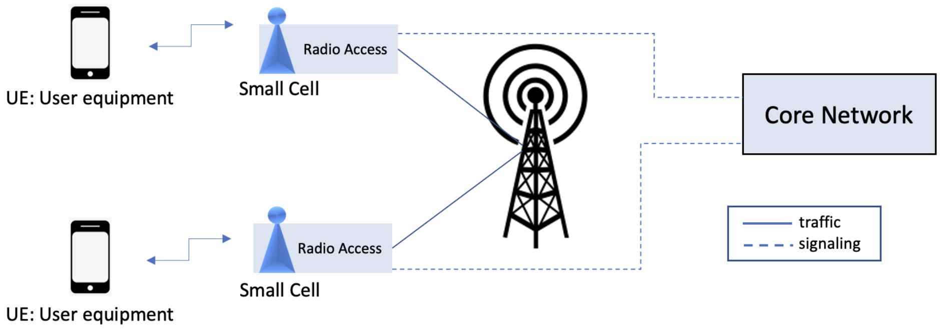


FIGURE 3.1: Local routing in 5G wireless network.

In Table 3.1, the 5G wireless used radio millimeter bands in the 30 GHz to 300 GHz range. By using small cells, the deployment of 5G with millimetre wave-based carriers and combined with Beamforming technology can improve overall coverage area and can deliver high-speed coverage with low latency. The 5G uses a scalable

Orthogonal Frequency-Division Multiplexing (OFDM) framework that can decrease latency to one millisecond. Comparing with 4G latency, the 5G's latency is estimated to be 60 to 120 times faster. Moreover, the 5G can provide better connections and achieve high throughput with more effective user tracking.

TABLE 3.1: Evolution of systems from 1G to 5G.

Features	1G	2G	3G	4G	5G
Start/Devlopment	1970/1984	1980/1999	1990/2002	2000/2010	2010/2015
Technology	AMPS,NMT,TACS	GSM	WCDMA	LTE,WiMax	MIMO,mmWaves
Frequency	30 KHz	1.8 GHz	1.6-2 GHz	2-8 GHz	30-300 GHz
Bandwidth	2 kbps	14.4- 64 kbps	2 Mbps	2000 Mbps to 1 Gbps	1 Gbps and higher
AccessSystem	FDMA	TDMA/CDMA	CDMA	CDMA	OFDM/BDMA
Core Network	PSTN	PSTN	Packet Network	Internet	Internet

The overview of the 5G is shown in Fig. 3.2. The 5G system employs similar elements to previous generations, including UE, comprising a Mobile Station and a Universal Subscriber Identity Module (USIM), the Radio Access Network (NG-RAN), and the 5G Core Network. The primary entity within the NG-RAN is the gNB, where "g" denotes "5G" and "NB" signifies "Node B," a term inherited from 3G onwards to denote the radio transmitter. The AMF/UPF entity depicts the 5G core network: the User Plane Function (UPF) manages user data, while in the signaling plane, the Access and Mobility Management Function (AMF) facilitates access to the UE and the RAN.

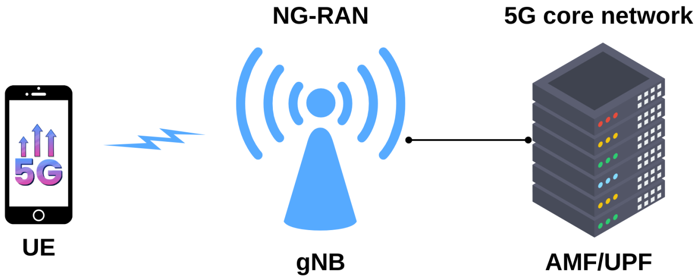


FIGURE 3.2: Overview of the 5G.

The 5G core network architecture serves as the foundation of the latest 5G specification, catering to the heightened throughput demands inherent to 5G technology. The 3rd Generation Partnership Project (3GPP)'s standardization of the 5G core network architecture is designed to meet the rising demands for higher data throughput, lower latency, and improved reliability, essential for the diverse applications and services 5G is expected to support. Defined by 3GPP, the new 5G core adopts a cloud-native, service-based architecture (SBA) that covers all aspects of 5G operations, including authentication, security, session management, and traffic consolidation from connected devices. It also prioritizes Network Functions Virtualization (NFV) as a core design principle, wherein virtualized software functions are deployed utilizing the Multi-Access Edge Computing (MEC) infrastructure.

An illustration of this bus-based 5G core network architecture is presented in Fig. 3.3. The specifics of this architecture are detailed in the 3GPP Technical Specification 23.501 [40]–[42].

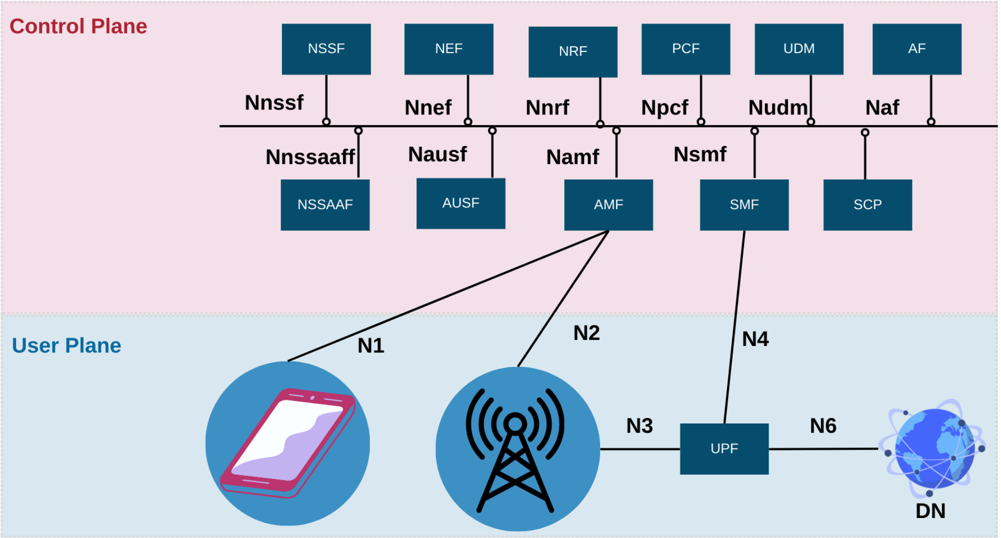


FIGURE 3.3: The 5G core network architecture.

The 5G core network comprises network function services divided into control and user plane domains. A network function service is a specific capability offered by a Network Function (NF), known as the NF Service Producer, to other authorized NFs, referred to as NF Service Consumers, via a service-based interface. This provision allows for the sharing and utilizing particular network functionalities among different network components through standardized interfaces. It encompasses a variety of services, each built from numerous procedures, as described in following.

- **Authentication Server Function (AUSF):** The AUSF serves as an authentication server. Primarily, it incorporates the functionality of an EAP (Extensible Authentication Protocol) authentication server while also functioning as a repository for keys. It supplies the requesting NF with the necessary keying material.
- **Access and Mobility Management Function (AMF):** The AMF is responsible for handling a wide range of tasks within the network, including terminating NAS signaling, or Non-Access Stratum signaling, conducting NAS ciphering and integrity protection, and managing registration, connection, and mobility. It also oversees access authentication and authorization, as well as the management of security contexts. Additionally, the AMF encompasses the Network

Slice Selection Function (NSSF) and serves as the endpoint for RAN control plane interfaces (N2).

- **Session Management Function (SMF):** The SMF is responsible for managing sessions, including their establishment, modification, and termination. It handles the allocation and management of IP addresses for UE, provides DHCP functionalities, and manages the termination of NAS signaling related to session management. Additionally, the SMF is in charge of downlink data notifications and configuring traffic steering for the User Plane Function (UPF) to ensure the correct routing of traffic.
- **Network Exposure Function (NEF):** The NEF plays a vital role in facilitating and securing the exchange of capabilities and events between the external applications and the 3GPP network, including translating information into and out of the network. As an API gateway, it grants external entities like enterprises or partner operators the ability to monitor, provision, and enforce application policies for users within the operator's network.
- **NF Repository Function (NRF):** The NRF is discovering instances of network functions within the network. Upon receiving a discovery request from a NF instance, the NRF identifies and provides information on the relevant NF instances. This functionality, not available in 4G networks, enhances the system's efficiency and adaptability. Moreover, the NRF is responsible for maintaining and supporting profiles of these NF instances along with their supported services. It also oversees the service-based interfaces and management and maintenance tasks within the network, ensuring seamless operation and communication between various network components.
- **Policy Control Function (PCF):** The PCF implements a unified policy framework, delivering policy rules to Control Plane (CP) functions and accessing subscription information from the Unified Data Repository (UDR) for making policy decisions. This framework encompasses network slicing, roaming, and mobility management, offering a comprehensive approach to policy management across various network scenarios. The PCF shares similarities with the Policy and Charging Rules Function (PCRF) found in 4G networks, extending its functionalities to meet the advanced requirements of 5G, including enhanced support for diverse network architectures and services.
- **Unified Data Management (UDM):** The UDM is responsible for storing subscriber data and profiles, generating Authentication and Key Agreement (AKA) credentials, handling user identification, authorizing access, and managing

subscriptions. This component plays a crucial role in the secure and efficient management of subscriber information and access within the network, ensuring that users are authenticated and authorized to access services according to their subscription details.

- **Application Functions (AF):** The AF acts as an application server capable of interacting with other control-plane NFs. Designed to serve various application services, AFs can be owned by either the network operator or trusted third parties. An example includes the AF for an Over-the-Top (OTT) application provider, which has the ability to influence routing and direct its traffic towards external edge servers. For services deemed trusted by the operator, the AF can directly access NFs. In contrast, untrusted or third-party AFs are required to access Network Functions via the Network Exposure Function (NEF), ensuring a secure and controlled interaction with the network's core functions.

- **Network Slicing Selection Function (NSSF)** The NSSF is designed to identify and select the most suitable network slice for the service requested by the user. This ensures that the specific requirements for each service, such as bandwidth, latency, and reliability, are met by matching the user's needs with the capabilities of an appropriate network slice. The NSSF optimizes resource utilization and enhances user experience by dynamically allocating network resources based on service demands.

- **Network Slice Specific Authentication and Authorization (NSSAA):** The NSSAA is a mechanism designed to provide separate authentication and authorization for each network slice. This is crucial in a 5G environment where different slices might cater to vastly different service requirements and security levels. The initiation of NSSAA depends on subscription details obtained from the UDM and the operator's policy. This process can be activated when the UE signals its capability to support this feature, ensuring that access to network slices is securely controlled and aligned with both the user subscription and the specific security requirements of each slice.

- **Service Communication Proxy (SCP):** The SCP enhances the core network by providing routing control, resiliency, and observability, enabling operators to securely and efficiently manage their 5G networks. SCP addresses various challenges introduced by the new Service-Based Architecture (SBA) in the 5G core by leveraging IT service mesh technology, such as ISTIO, and incorporating essential features to adapt it for 5G. These enhancements make the SCP an integral component in the operation and maintenance of the 5G network infrastructure, ensuring smooth communication and service delivery across the network.

- **User Plane Function (UPF):** The UPF is responsible for routing and forwarding packets, conducting packet inspections, and managing Quality of Service (QoS). It serves as the external Packet Data Unit (PDU) session interconnection point to the Data Network (DN) and acts as an anchor point for mobility across both intra- and inter-Radio Access Technologies (RAT).
- **Data Network (DN):** The DN is the external data network that provides access to operator services, third-party services, and more. It serves as a gateway for users to reach a wide array of services and internet resources outside the confines of the mobile operator's own network, facilitating connectivity and data communication between users and the global internet or specific external services.

3.2 The "Non-Stand Alone" (NSA) and the "Stand-Alone" (SA) in 5G modes

Standalone 5G, or 5G SA, refers to a deployment model in which a mobile operator constructs a comprehensive 5G network by exclusively utilizing 5G-specific radio and core network components. This approach enables the full realization of 5G capabilities, including high data rates, low latency, and network slicing, providing a pure 5G experience. In contrast, non-standalone 5G, or 5G NSA, combines a 5G radio network with the existing 4G LTE core network infrastructure, known as the EPC. This model allows operators to quickly launch 5G services by leveraging their existing 4G network assets, facilitating a smoother and more cost-effective transition to 5G by utilizing the 5G radio access while still relying on the core network functionalities of 4G. The comparison of on-standalone 5G architecture with standalone 5G is shown in Fig. 3.4.

Many operators initially opt for NSA mode in their 5G deployment strategy to leverage their existing infrastructure and swiftly deliver immediate benefits to users. However, as the 5G ecosystem matures and the demand for more advanced services increases, operators are anticipated to transition to SA mode. This transition entails substantial upgrades to the network architecture, including the implementation of a 5G core network capable of supporting next-generation functionalities.

NSA and SA modes present distinct strategies in the deployment of 5G, each carrying its own advantages and strategic implications. NSA mode offers a rapid and cost-effective pathway to enhance data services by leveraging existing LTE infrastructure. On the other hand, SA mode represents a transformative shift towards a future where networks are more flexible, capable, and prepared to facilitate a fully interconnected world. This mode lays the groundwork for a more comprehensive and advanced 5G ecosystem.

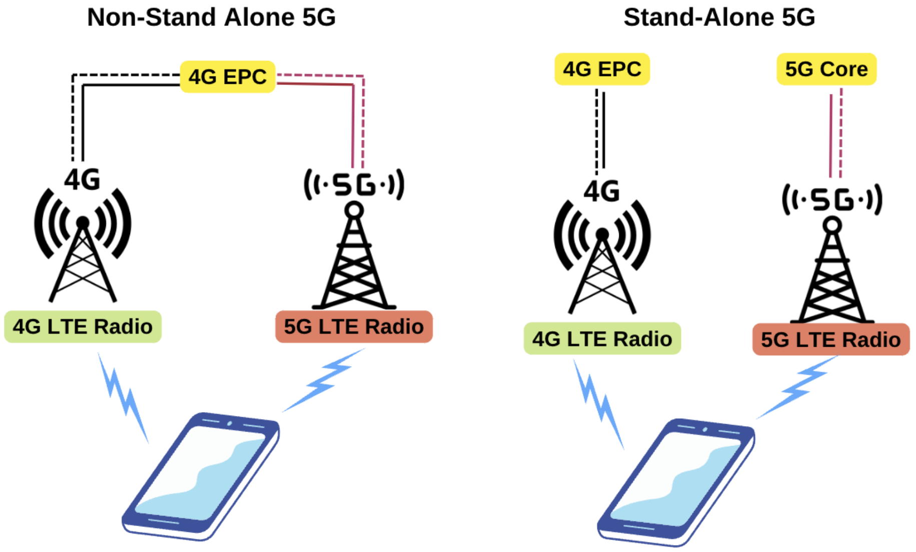


FIGURE 3.4: Compare non-standalone 5G architecture with standalone 5G.

3.3 Architectural Innovations in 5G

The 5G networks enabled with network slicing architecture can offer on-demand tailored connectivity to their users that are following to Service Level Agreement (SLA). Such customized network capabilities comprise latency, data speed, latency, reliability, quality, services, and security can be flexible for the best performance.

The NFV and SDN are very important in 5G wireless networks for increasing network performance and reducing the costs.

Network Function Virtualization (NFV)

The NFV separated software from hardware by changing from various network functions like firewalls, load balancers and routers to virtualized instances running as software. For example, if a user requires to add a new network function, the service provider can create a new virtual machine to work as that network function without using new hardware for making that network function. The NFV architecture is developed by the European Telecommunications Standards Institute (ETSI) [43], [44].

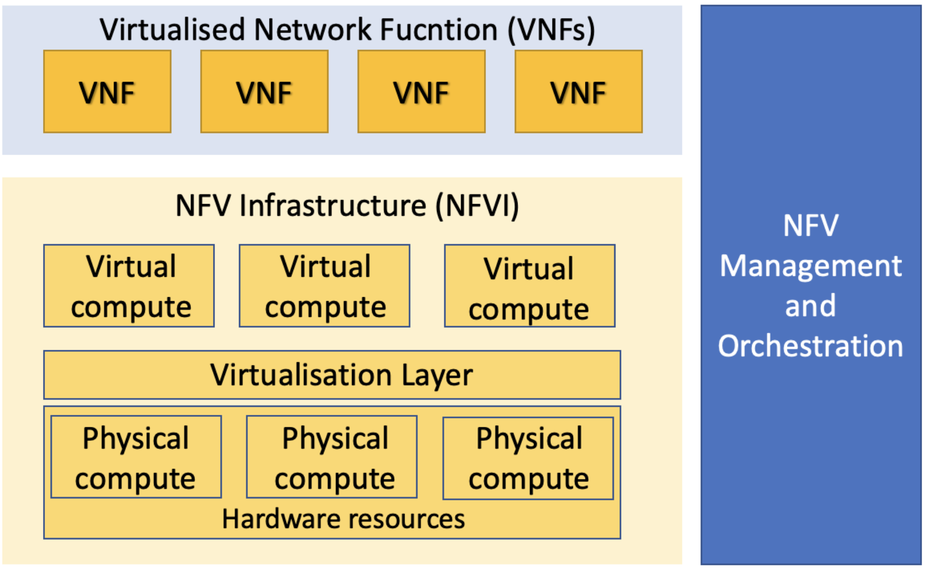


FIGURE 3.5: High-level ETSI NFV framework.

The ETSI NFV framework has three main working domains as shown in Fig. 3.5.

- **Virtual Network Functions (VNFs):** VNFs are individual network functions that have been virtualised such as firewalls, Evolved Packet Core, etc.
- **NFV Infrastructure (NFVI):** NFVI consists of hardware resources like computing servers and network switches, virtual resources know as "Virtual Machines" (VMs). A virtualisation layer (the "hypervisor") is connecting between the two resource.
- **NFV Management and Orchestration (NFV MANO):** NFV MANO is the framework for management and orchestration of all resources in the NFV environment.

Software-Defined Networking (SDN)

The SDN has the main idea of separating the control plan and data plan and enabling external control of data through a logical software component called the SDN controller.

The SDN centralized controller manages the network resource and acts as the Networking Operating System (NOS). It has a global view of the network by monitoring and collecting the real-time network state and configuration data such as a global view of the network by monitoring and collecting the real-time network state and configuration data [45].

SDN has several limitations because mobile devices' computing capabilities and resources have limited resources, but it has advantages such as resource sharing and session management. The SDN will be explained in more details in Charter 4.

5G Network Slicing

The 5G NS concept was initially developed by Next Generation Mobile Networks (NGMN) as shown in Fig. 3.6. The network slicing process is divided into three main layers. The Service Instance layer represents a service (end-user service or business services) which is provided by application provider or mobile network operator. The Network Slice Instance layer is a set of network functions and resources which provide the network slice instance to accommodate network characteristics required (ultra-low-latency, ultra-reliability) by the Service Instances. The Resource layer comprises of physical resources and logical resources for slice deployment [46], [47].

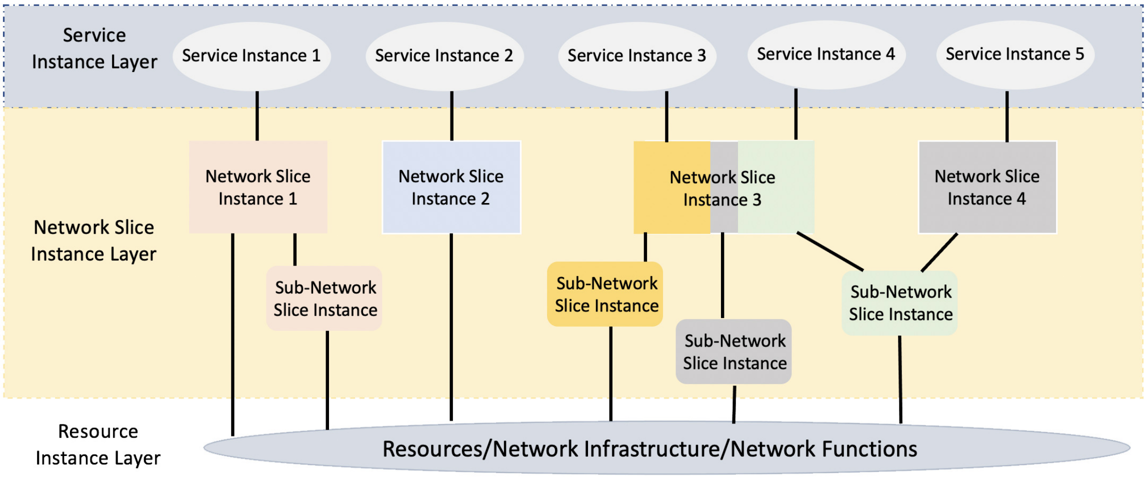


FIGURE 3.6: NGMN network slicing concept.

The SDN network slicing architecture is provided by the Open Network Foundation (ONF). In SDN network environment, the main components of SDN architecture are resources and control. In Fig. 3.7, the interfaces between the SDN architecture components show client-server relationships. The SDN controller dynamically manages network slice by using a set of policies and grouping slices that belong to the same context [46], [48]. The ONF SDN network slicing architecture has the following components.

- **Client Context:** It has all information that the controller needs to communicate with a client. The components of client context are client support and virtual resources for responding to end user's requests.
  - Client support: It contains support information of client operation.
  - Resource group: It contains the customized view of all resources that the controller offers to client based on service demands and facility.
- **Server Context:** It has all information that the controller needs to interact with a set of underlying resources.

- **Administrator:** The administrator configures all controllers, servers and client context including installation of their associated policies.
- **Application/SDN Controller:** This controller can control the slice by using server context.

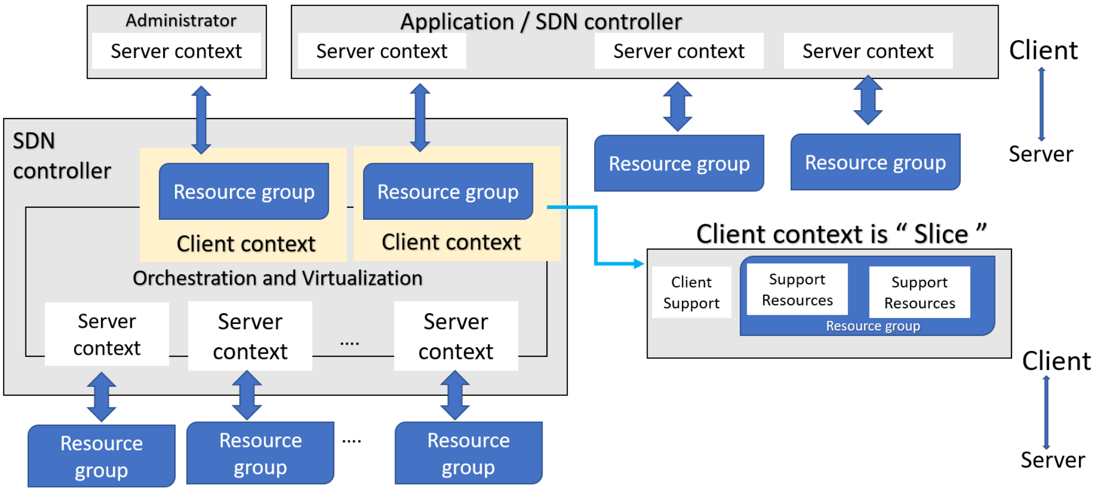


FIGURE 3.7: ONF SDN network slicing architecture.

Multi-Access Edge Computing (MEC)

The MEC is an essential component of 5G architecture. The MEC enables IT and cloud computing that brings the applications from a centralized data center to the network edge. The advantage of MEC is the low latency, high bandwidth and real-time access to Radio Access Network (RAN) information. The MEC offers an open radio network edge platform, facilitating multi-service and multi-tenancy by allowing authorized third parties to use of processing system and the storage system, introducing vertical business segments and services for consumers and enterprise customers. It will be used in video analytics, IoT, data caching, augmented reality [49].

Multi-access Edge Computing (MEC) offers several key benefits that enhance the performance and efficiency of network services:

Low Latency: MEC processes data close to where it is generated rather than at distant data centers, significantly cutting down on latency. This is particularly important for applications that require real-time decision making, such as autonomous driving, real-time analytics, and augmented reality, where even small delays can impact performance and outcomes.

Improved Bandwidth Utilization: By reducing the necessity of sending large volumes of data to and from centralized data centers, MEC helps alleviate network congestion and minimize bandwidth consumption. This is especially advantageous in densely populated urban areas or during large events where network traffic is high.

Localized Content and Application: MEC enables the localization of content and applications, allowing data to be processed closer to the user. This benefits content delivery networks (CDNs) by optimizing services like video streaming, which are enhanced by serving content from a location nearer to the user, thereby reducing load times and buffering.

Context-Aware Services: With its proximity to users, MEC can utilize real-time, local context information such as user location to offer personalized and context-aware services. This capability improves the user experience by delivering services that are tailored to individual preferences and situational needs, making them more relevant and timely.

Beamforming

Beamforming is a signal processing technique employed in 5G networks to precisely steer the transmission and reception of radio signals using antenna arrays as shown in Fig. 3.8. By concentrating the signal towards targeted users rather than broadcasting it indiscriminately, this technology significantly boosts the efficiency and effectiveness of wireless communication. Beamforming assumes a pivotal role in the deployment of 5G networks, which operate across conventional lower frequencies as well as higher millimeter-wave frequencies. While the latter can accommodate substantial data payloads over short distances, they are prone to interference and attenuation, making beamforming crucial for optimizing their performance [50], [51].

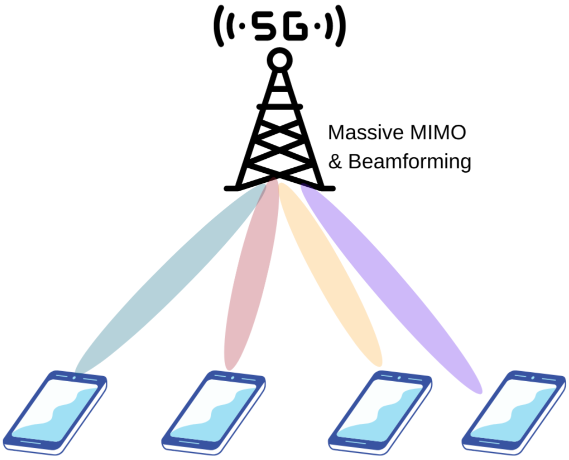


FIGURE 3.8: Beamforming implementation.

Chapter 4

Software Defined Networking (SDN)

In this chapter is presented SDN, SDN architecture, advantages and limitations of SDN and applicability of SDN.

4.1 SDN Architecture

The SDN is a new networking paradigm that decouples the data plane from control plane in the network and promotes (logical) centralization of network control that have ability to program the network. This separation can be flexible and centralized management with a global view of entire network. In Fig. 4.1 is shown the traditional network and SDN approaches. In traditional network, the control plane (which decides how to handle network traffic) and the data plane (which actually moves packets based on those decisions) are tightly integrated within each network device such as routers and switches. This integration means that each device operates independently, with its own configuration and management required. Thus, the traditional networks are hard to manage and control since they rely on physical infrastructure. It is difficult to configure the network according to predefined policies and to reconfigure it to respond to faults, load, and changes because the processes must be based on the setting of each device and making controlling and operation on each device.

In contrast, SDN creates virtualized control plane with intelligent management decisions, when network administrators can control and reconfigure the overall network by managing on virtualized controller. Thus, the SDN is easy to manage and provide network software-based services from a centralized control plane. The SDN control plane is managed by SDN controller or cooperating group of SDN controllers [52]–[56]. Also, with its centralized control and abstracted view of the network, SDN can scale more efficiently. Network administrators can quickly deploy and manage new services across the entire network through software changes at the controller level, without needing to manually configure individual hardware devices.

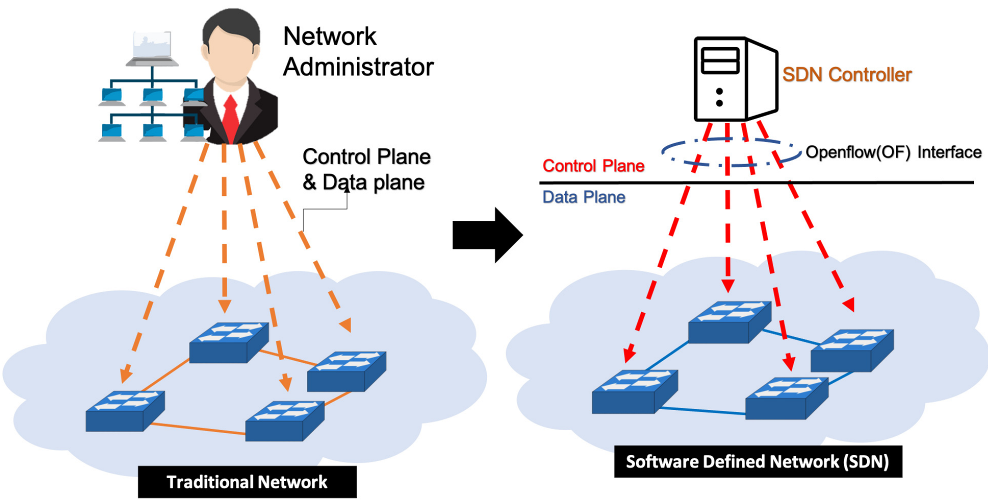


FIGURE 4.1: Comparison of traditional network and SDN.

The SDN structure is shown in Fig. 4.2. The control layer, the application layer and the infrastructure layer with the northbound and southbound APIs (Application Programming Interfaces) between those layers.

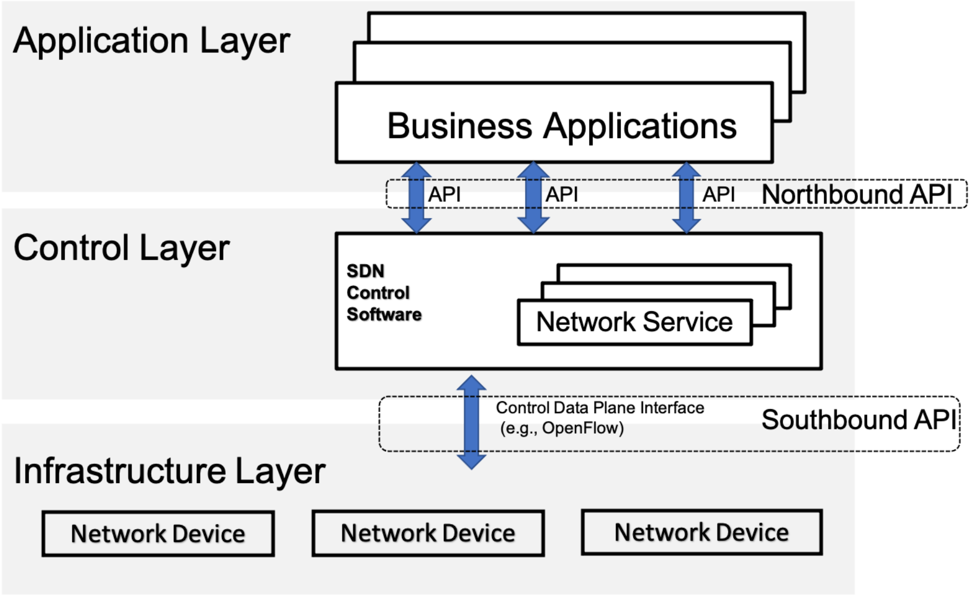


FIGURE 4.2: Simplified view of an SDN architecture.

Application Layer

The application layer builds an abstracted view of the network by collecting information from the controller for decision-making purposes. The types of applications are related to network configuration and management, network monitoring, network troubleshooting, network policies and security. For example, it can be used for managing handovers or determining the best access, at any given time, for a multi-technology terminal. This layer contains the operating system for the Cloud. The best-known cloud system is Open Stack, a Cloud management system that controls large sets of resource offering processing power, storage and network resources.

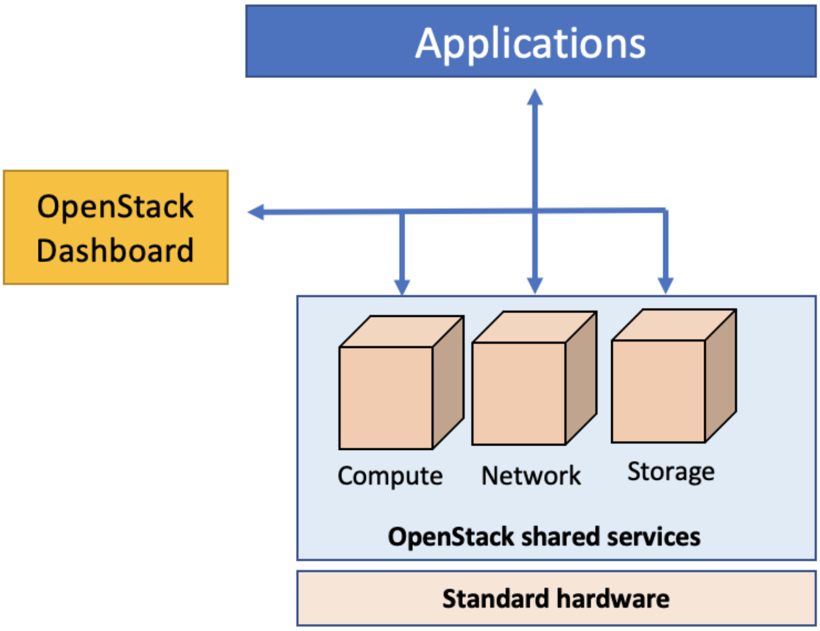


FIGURE 4.3: Open Stack architecture.

The Open Stack architecture is shown in Fig. 4.3. Open Stack is open standard cloud computing software with an Apache license. It contains a lot of modules developed in parallels such as Nova for computation, Swift for storage, Glance for the imaging service, Dashboard for the settings and control panel.

Northbound Interfaces

The northbound interfaces allow communication between the control layer and the application layer and can provide a lot of possibilities for networking programming. When it can describe the needs of the application. It will pass commands and information to the control layer and make the controller creates the best possible software network with suitable qualities of service and acceptable security. When the network problem happens, the controller can make the necessary management to resolve problems by using that software network. The communication packet contains the information necessary for the configuration, operations and measurements. The basic protocol for those communications is based on the Representative State Transfer (REST) API. This protocol is integrated into numerous Cloud management systems, and in particular in the interfaces of most of these systems, such as Open Stack, the service providers and the API Virtual Private Cloud (VPC).

Control Layer

The control layer receives instructions or requirements from the Application Layer. It contains the controllers that control the data plane and forward the different types of rules and policies to the infrastructure layer through the Southbound interfaces. When the control layer receives policy rules and the description of the applications, it deduces the actions needed on the networking equipment. The actions can be made on routers, switches, firewalls, load balancers, virtual VPNs and other hardware. In the control layer, the controller consists of many modules for different handle functions necessary in the operation of the network. For example, the load balancer can determine the best paths on the data plane and should optimize the user demands and user applications as shown in Fig. 4.4.

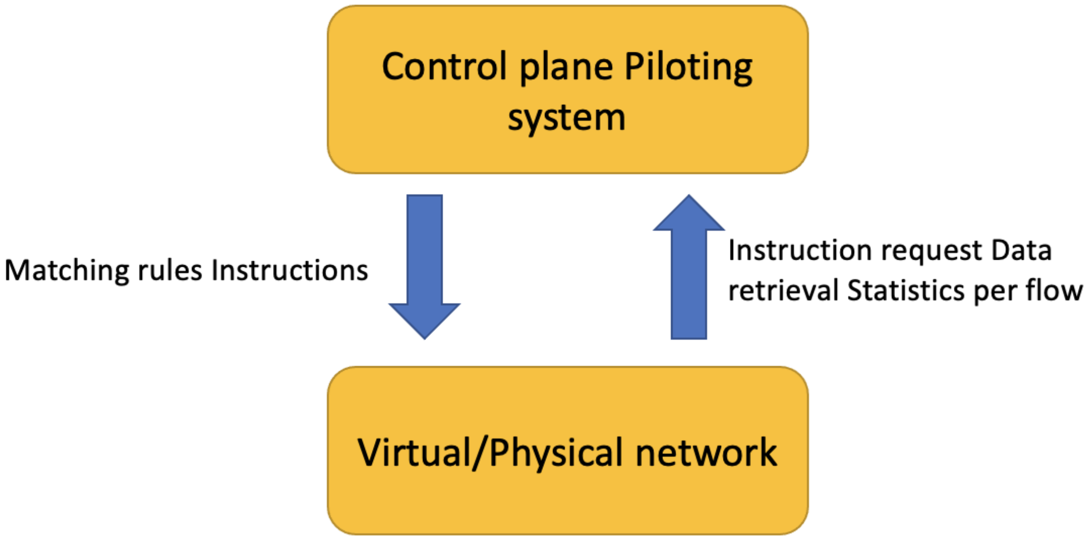


FIGURE 4.4: Load-balancing protocol.

Southbound Interfaces

The southbound interfaces allow connection and interaction between the control plane and the data plane. The southbound interface is defined as protocols that allow the controller to create policies for the forwarding plane. The signaling of that protocol passes the configuration commands through this interface in one direction and the statistical information of network devices will be feedback to the control layer. In this interface, the accepted and used protocols are as follows.

- OpenFlow;
- I2RS (Interface to Routing Systems);
- Open vSwitch Data Base (OvSDB);

- Net Conf;
- SNMP;
- LISP;
- BGP.

The signaling of that OpenFlow protocol is illustrated in Fig. 4.5. This protocol has to determine the data streaming by matching several components such as addresses or port numbers and specify the actions on transiting data from the controller to the networking devices.

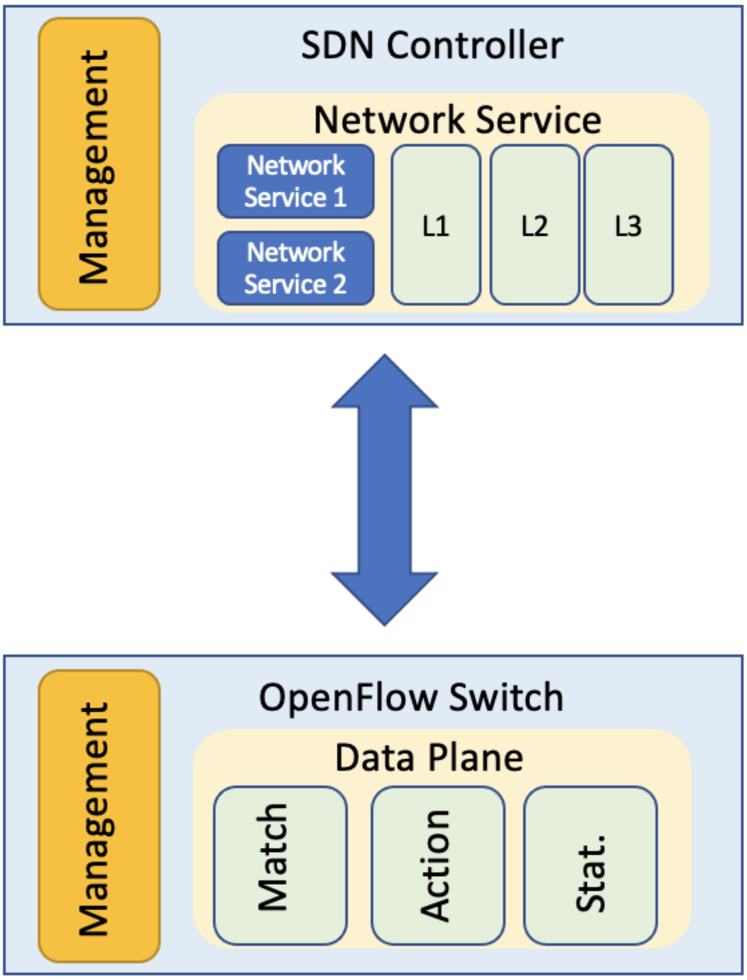


FIGURE 4.5: The signaling protocol OpenFlow.

OpenFlow Network

OpenFlow is a multivendor standard that can be programmed to identify, categorize and process packets from an ingress port based on many packet header fields. Also, it can drop or push the packets to a particular egress port or to the OpenFlow Controller. It was defined by the Open Networking Foundation (ONF) for implementing SDN in networking equipment. In Fig. 4.6 is shown the OpenFlow structure contains three main components: OpenFlow Switch, OpenFlow Controller and OpenFlow Protocol. The OpenFlow Protocol is the interface between OpenFlow Controller and OpenFlow switch.

- **The OpenFlow Switch:** The OpenFlow Switch is forwarding the packets and making the packet matching function which matches the incoming packets with an entry in the flow table and then directs the packet to an action box by controlling from the OpenFlow Controller. The action box has three fundamental actions: forward the packet out a local port, drop the packet and pass the packet to the OpenFlow controller.
- **The OpenFlow Controller:** The OpenFlow Controller is a flow control management software in the SDN environment. Also, it serves as a sort of operating system for the network, because all communications between applications and devices have to go through the controller. The OpenFlow Controller is responsible for programming all packets matching and forwarding rules in the switch.
- **The OpenFlow Protocol:** The OpenFlow protocol consists of two sets of messages: a set of messages and a corresponding set of messages. Both of them are sent between OpenFlow Controller and OpenFlow Switch through OpenFlow protocol. The messages allow OpenFlow controller to control the OpenFlow switch for fine-grained control over the switching of user traffic such as modifiying and deleting flows.

The OpenFlow instructions are built as “flows” that consist of packet match fields, flow priority, various counters, packet processing instructions, flow timeouts and a cookie. It is transmitted from an OpenFlow Controller to an OpenFlow Switch and is organized in flow tables and processes an incoming packet in multiple “pipelined” tables before exiting an egress port.

Infrastructure Layer

The infrastructure layer receives orders from SDN controller and sends data among them. This layer represents the forwarding devices on the network such as routers, switches and load balancers.

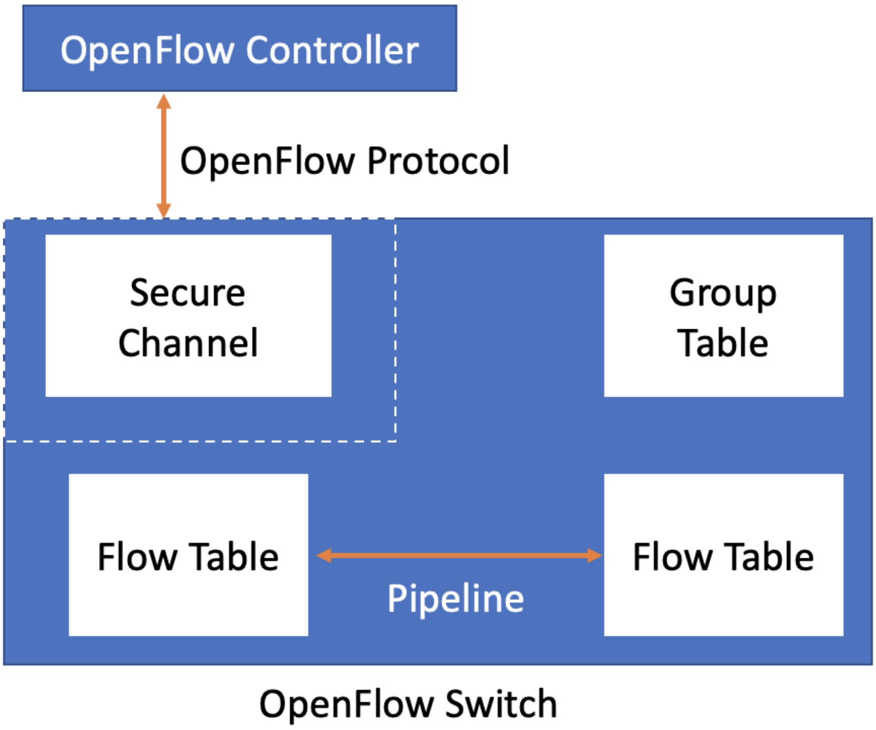


FIGURE 4.6: OpenFlow structure.

4.2 Advantages and Limitations of SDN

The SDN can manage the network while enabling new services. In congestion traffic situation, the management system can be flexible, allowing users to easily control and adapt resources appropriately throughout the control plane. Mobility management is easier and quicker in forwarding across different wireless technologies (e.g.5G, 4G, Wifi and Wimax). Also, the handover procedure is simple and the delay can be decreased [57]. But, when the administrator wants to implement SDN protocol and SDN controller, the entire network infrastructure needs to be changed. If the SDN controller fails, the entire system also fails.

4.3 Applicability of SDN

The applicability of SDN has been used in a wide range of networking. It can be applied also in many others such as enterprise networks, WLANs and heterogeneous networks, optical networks and the IoT. This section presents only two characteristic examples for understanding how SDN can be beneficial: data centers and cellular networks.

Data Center Networks

The data center networks need to find ways to support a lot of servers and virtual machines. In traditional data centers, it has to carefully design and make manual configuration of underlying network such as defining the preferred routes for traffic. When it is required to be scale-up, the manual configuration becomes a very challenging and error-prone task such as extending the size of the network. It is hard to fulfill the requirement. But the SDN can fill these gaps in network management by decoupling the control plane from data plane, then forwarding devices become much simpler and cheaper. Also, all control logic become one logically centralized entity and no need for placing middleboxes in the network because policy enforcement can be achieved by the controller

Cellular Networks

For responding the demands of the increasing traffic and the limited wireless spectrum for accessing the network, the cell sizes of the access network tend to get smaller. This increases the interference among neighboring base stations and lead to a high number of handovers which interrupt the call and degradate the throughput. To solve these problems, the cellular networks will use the SDN controller, which can act as an abstract base station to simplify the operations of load and interference management. Moreover, it no longer requires the direct communication and coordination of base stations. The centralized controller that has all views of the entire network allows network equipment to become simpler and makes the network more flexible and easier to manage in operations like routing, real-time monitoring, mobility management, access control and policy enforcement. It also can be assigned to different cooperating controllers.

Chapter 5

Admission Control, Handover, and Radio Access Technology

In this chapter is described admission control which is the main approach for the proposed system.

5.1 Introduction to Call Admission Control (CAC)

Call Admission Control (CAC) is an important application of resource management which makes decision to accept or deny a new service request from user by considering available resource to handle minimum requested QoS [58]. Moreover, another of CAC's objective is to guarantee the continuity of current active connections.

The CAC algorithm have two types of decision errors. The accepting error happens when the CAC algorithm decides to accept a new service but it should be rejected. Because of that, the QoS will be degraded or even dropped. The second one is rejecting error that happens when CAC algorithm decides to reject a new service but it should be accepted.

5.1.1 Call Admission Control Description

The CAC is a resource management function for regulating traffic volume in voice communications, which regulates network access to ensure QoS provisioning. In Fig. 5.1, when a new user requests a new connection, the CAC policy takes the call request, views the traffic condition and decides whether or not to accept the call request. The CAC is used in the call setup step and applies only to real-time media traffic multimedia traffic characteristics. The decision for CAC is a very challenging issue due to user mobility and the limited radio spectrum [59]. If the network has sufficient bandwidth to guarantee voice quality for an incoming call, the CAC will accept a new call and establish a call connection but if it has not enough bandwidth to guarantee voice quality, the call request will be rejected [60], [61].

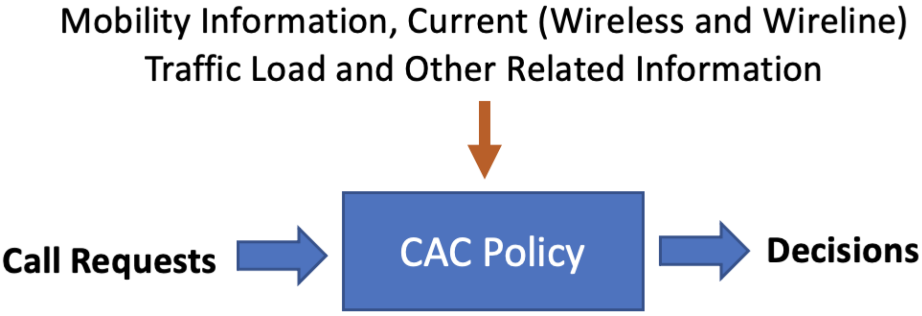


FIGURE 5.1: CAC decision process.

Challenges in CAC

For CAC, there are many challenges in the wireless and the combined wireless & wireline environments in various network conditions because of the limited radio spectrum, user mobility and usable bandwidth due to time-varying channel conditions. Network providers expect that CAC has the ability to ensure a minimum transmission rate, either limiting the network load by minimizing the transmission rate degradation and maximizes the revenue by minimizing the penalty incurred by dropping an existing call and carrying out a channel reassignment.

Categories of CAC Mechanisms

The CAC Mechanisms have three main categories [62]. These QoS mechanisms comprise tools such as queueing, policing, traffic shaping and packet marking.

- **Local CAC mechanisms** consider the local conditions of node on the outgoing gateway.
- **Measurement-based CAC techniques** will send probes to the destination IP address in the packet network. That probes will return with the information on the condition of network. The CAC decision will consider that information for accept or reject.
- **Resource-Based CAC Mechanisms** have two types of Resource-Based CAC Mechanisms. First type will calculate wanted resources and/or available resources. Second type will reserve resources such as necessary bandwidth on every node and every link between for the call.

The poor QoS performance can occur in the network system without CAC because of no policy for managing resources and insufficient resource for users. For example, from Fig. 5.2, the third call will cause poor quality for all calls in VoIP network without CAC.

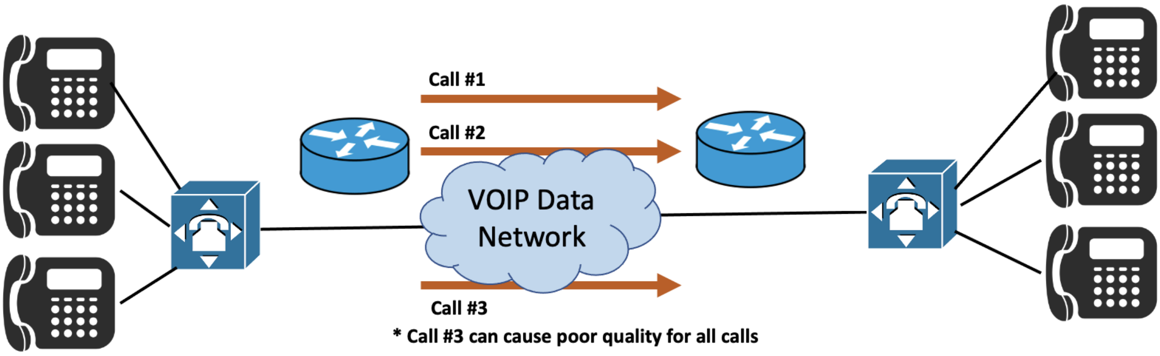


FIGURE 5.2: VoIP network without CAC.

5.1.2 Slice Admission Control

Slice Admission Control (SAC) is essential for efficient management of network resources in the 5G network. In Fig. 5.3, The available resources dictate slice admission in the network resource pool. Slice requests may be queued while the implemented admission algorithm queries admissibility fitness considering available resources.

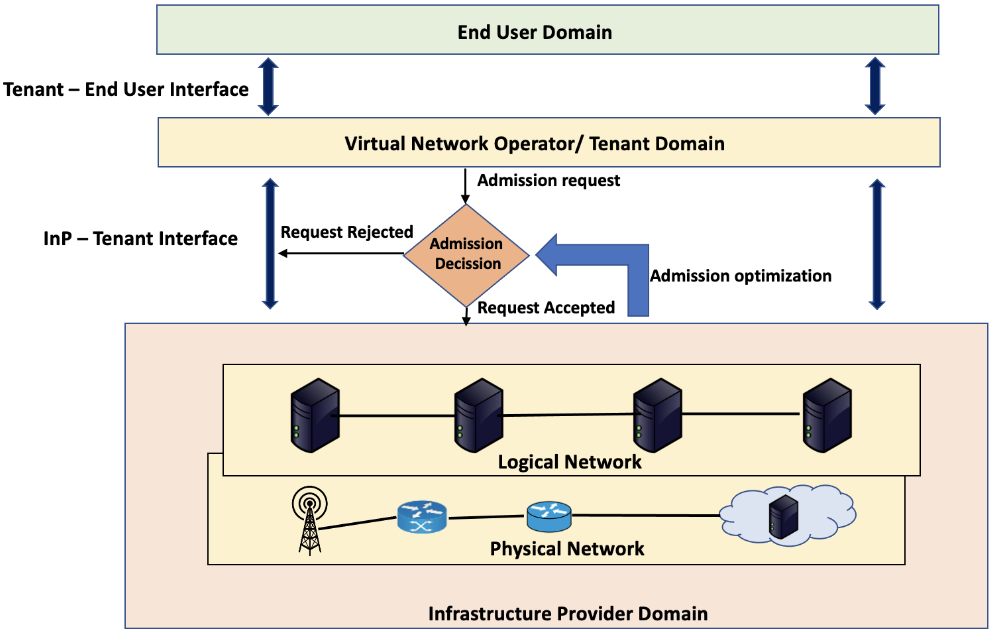


FIGURE 5.3: Slice admission control framework.

The four main objectives of slice admission control algorithms [63]:

- **Revenue Optimization:** For making maximize revenue, any slice provider will decide to apply admission control algorithm to allocate network resources. For example, CAC algorithm may prioritize latency and high bandwidth for high revenue.

- **QoS Control:** Slice admission control algorithm will admit requests where QoSs can be guaranteed. Slice request can be reject for reserving more resource to make good QoS performance.
- **Inter-slice Congestion Control:** The congestion may occur when slice requests are directly sending to the orchestrator for virtual function instantiation without a slice admission control. So, slice provider will deploy slice admission control for slice management.
- **Slice Fairness Assurance:** For reducing unfairness during selection, admission control algorithms are applied for the reasonable distribution of slice requests such that no single slice type is repeatedly admitted at the expense of other slice requests in the case of slice priority is not the main consideration.

Slice Admission Strategies

For achieving the objective, slice admission algorithm can be designed based on a specific strategy or intelligent algorithm for flexibility and better performance in different scenarios. The specific strategy can be divide into five strategies. First, the first-come-first-served strategy will manage the slice requests as they arrive [64]. Second, the priority-based strategy will consider the category of slice requests. When slices have a high priority, slice request will have a high acceptance possibility. Third, the greedy-based strategy proposed by Challa et al. [65] deploys a partial adaptive greedy (PAGE) algorithm to maximize revenue while minimizing SLA violation for customers with different willingness to pay indices. Fourth, the random strategy manages the slice requests randomly for reducing unfairness during admission control but it is no optimized. Fifth, optimal strategy will define CAC objective and perform a complete optimization by using machine learning techniques.

Characteristics of QOS in 5G Wireless Networks

Before CAC will decide to accept or reject the request, it consider the characteristics of QoS in 5G wireless networks. The characteristics of QoS are dictated by three different usage scenarios which have been identified as eMBB, URLLC and mMTC. For example, the eMBB services require high bandwidth and sustained high capacity network connections in 5G wireless network. These services have characteristics of QoS in terms of Guaranteed Bit Rate (GBR) or Non-Guaranteed Bit Rate (NGBR), packet delay budget, and packet error rate as shown in Table 5.1 [66].

TABLE 5.1: Characteristics of QoS in 5G.

Resource Type	Packet Delay Budget	Packet Error Rate	Example Service
GBR	100ms	10^{-2}	Coversation Voice
GBR	50 ms	10^{-3}	Real Time Gaming
GBR	50 ms	10^{-2}	V2X Messages
Non-GBR	300 ms	10^{-6}	Video (Buffered Streaming)
Non-GBR	200 ms	10^{-6}	Mission Critical Data
Non-GBR	100 ms	10^{-6}	IMS signalling

5.2 Introduction to Handover

Handover, also known as handoff, is a process in telecommunication that allows a mobile device to maintain continuous and seamless service as it moves from one cell/slice area to another. This fundamental feature in mobile cellular networks ensures that an ongoing call or data session persists even when the user moves, traversing the coverage areas of different cell towers.

Many research works consider technologies such as SDN, NFV, Fuzzy Logic (FL) and intelligent algorithms. For example, in order to reduce the processing delay in the handover procedure, the QoS can be enhanced by applying FL in SDN [14]–[16]. However, in these papers, the authors consider only conventinal imput parametters such as Received Signal Strength (RSS), data transmission rate, battery charge or packet loss rate and delay.

In [67], the slices service resources is maintained during handover proceeding using three heuristics algorithms: Simple Algorithm, Greedy Handover Algorithm and Intelligent Handover Algorithm. The handover procedure can maintain the required services for each slice and the availability of slices when the handover will be activated. The handover problem is investigated also in [68] using reinforcement learning techniques. The authors make the assumption that a separate subset of BSs supports each slice. The goal is to minimize the long-term handover costs while maintaining user QoS. The handover cost is defined from the cost of switching NS, the cost of switching BS, the cost of switching BS and NS, the cost of creating a new NS. For e-Health 5G Use Cases, in [69], the authors introduced the Cloud-Network-Slicing Mobility Control (CNS-MC) approach to maintain the m-health UE experience during mobility procedure.

For V2X environment, the authors implement a V2X Slice Selection Function (SSF-V2X) as a SDN application to trigger inter-slice handover by considering service requirements and network constraints [70]. Also, in [71], the authors proposed a inter/intra slice handover management architecture called Connection Mode as A

Service (CMaaS). The CMaaS controller is used for the Inter-Slice Handover and Skipping Mode as A Service (SMaaS) is used for the Intra-Slice Handover to minimize the handover cost.

In [72], the authors consider inter-slicing handover security and reliability. They address security flaws in 5G network slicing from attack detection and localization algorithms that launch a Distributed Denial of Service (DDoS) during the inter-slicing proceeding to find the weaknesses point. During the inter-slice handover phase, the lengthy authentication process is abused to start a DDoS assault.

Handovers can be categorized into several types, depending on the nature of the network architecture and the direction of the movement [73]–[75]:

5.2.1 Intra-cell Handover

Intra-cell handover occurs within the same cell but involves switching the frequency or channel to improve the connection quality in Fig. 5.4. This type is less common and is mainly used for load balancing within the cell or to manage interference.

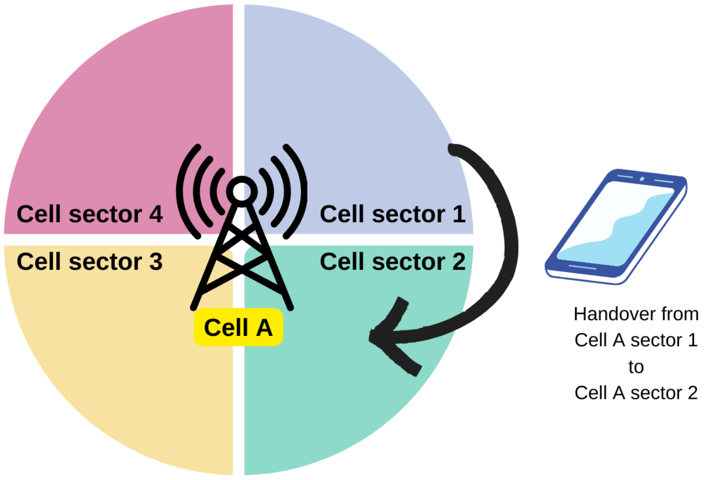


FIGURE 5.4: Intra-cell Handover.

5.2.2 Inter-cell Handover

Horizontal Handover (HHO), or Inter-cell Handover, will proceed when a mobile device moves from one cell to another within the same telecommunications system as shown in Fig. 5.5. It usually happens within a single layer of network technology.

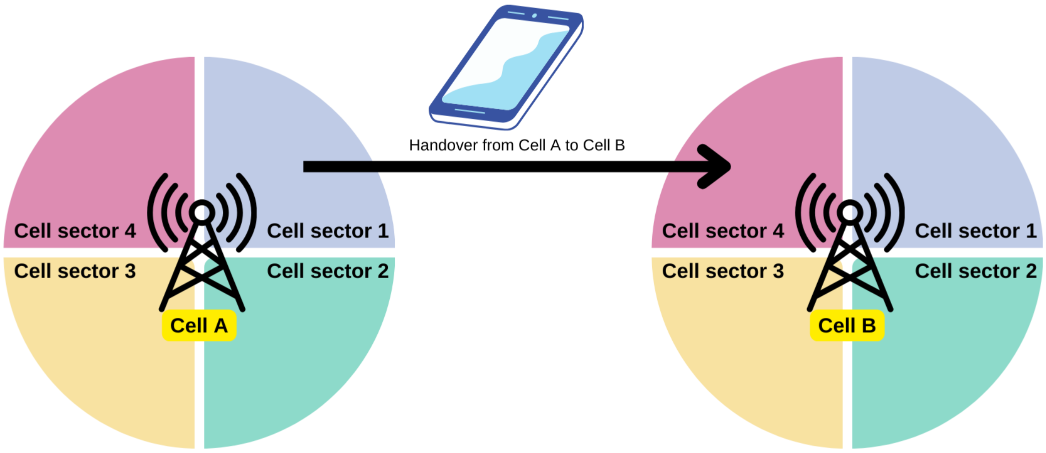


FIGURE 5.5: Inter-cell Handover.

Inter-cell handovers can be classified into two types based on the specific conditions: Hard handover and Soft handover.

Hard handover requires breaking the connection to the current cell before establishing a new connection with the next cell. This "break before make" process is commonly used in CDMA and WCDMA networks. However, it can sometimes lead to a noticeable drop in service.

Soft handover, or "make before break," allows a device to connect to the new cell before disconnecting from the current one. This type is possible in networks that support simultaneous connections to multiple base stations (like in some UMTS networks), significantly reducing the likelihood of dropped calls. Softer handovers are a subset of soft handovers, occurring when the channels involved are within the same cell but possibly using different frequencies.

5.2.3 Inter-RATs Handover

Vertical Handover (VHO), also known as inter-RAT handover, is a critical process in mobile communication systems that involves the transition of a mobile device's active connection from one type of network to another. This type of handover is referred to as "vertical" because it typically encompasses moving between different layers of network technologies that vary in speed, frequency, coverage, and protocol characteristics. For example, in Fig. 5.6, a VHO might occur when a device moves from a cellular network like LTE to a local Wi-Fi network, or from Wi-Fi back to LTE or another cellular technology such as 5G.

VHO is more complex than horizontal handover, which occurs within the same type of network (e.g., from one cellular tower to another), because it must manage different system architectures, service agreements, and connectivity parameters.

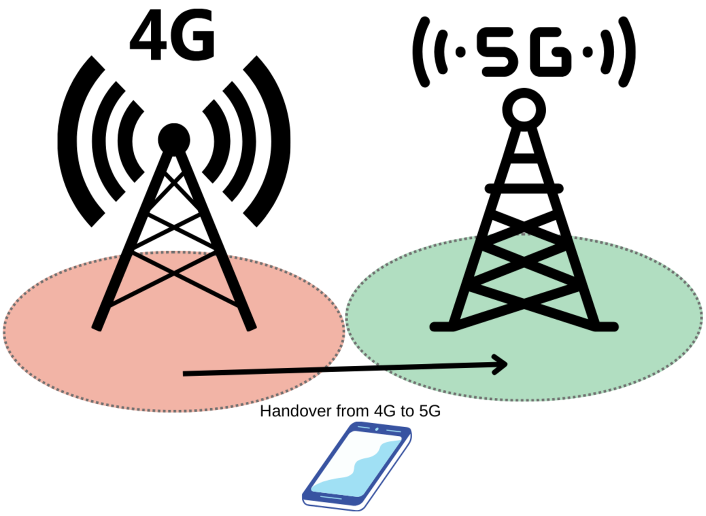


FIGURE 5.6: Inter-RATs Handover.

5.2.4 Inter-slice Handover

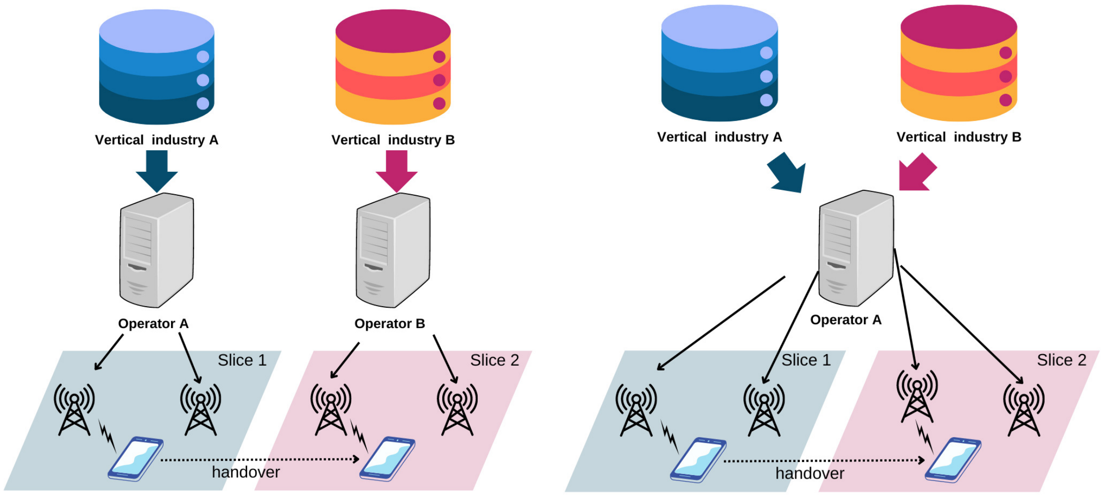
Inter-slice handover is the process of transferring a device's connection from one network slice to another within the same physical network infrastructure. This type of handover is crucial for maintaining the QoS and QoE when the device's service requirements change due to user activity or mobility patterns [76]. The efficient inter-slice handover between slices can fulfill the needs of certain high-real-time services, such as 5G-assisted drones and automatic driving.

In Fig. 5.7, this capability is essential for maintaining optimal service as users' contexts or service requirements evolve. Inter-slice handover is divided into three types as follows.

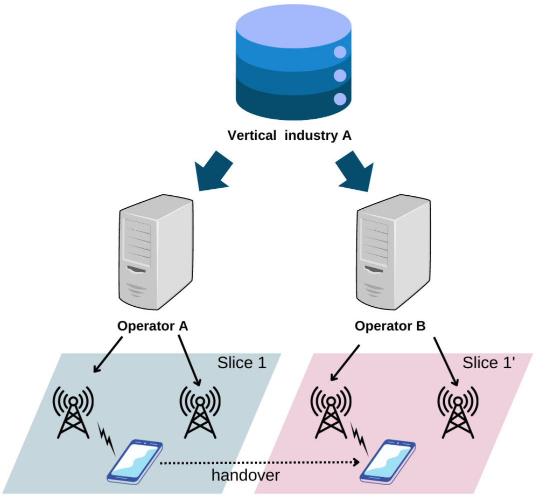
- **Different vertical industries with different operators:** Transitioning between slices dedicated to different industries (e.g., healthcare to automotive) managed by different network operators as shown in Fig. 5.7(a). This type of handover is complex due to the need for interoperability across operators' networks, each with its own set of policies, security standards, and service level agreements (SLAs).

- **Different vertical industries with same operators:** Handovers can occur between slices customized for different industries within a single operator's network as shown in Fig. 5.7(b). This means that within a network, various slices, each optimized for specific industries or use cases, can seamlessly hand over connections as users transition between different slices. This capability ensures that users maintain continuous service and experience consistent QoS across diverse sectors or applications, despite the specialized requirements of each slice. For instance, moving a connection from a slice serving IoT devices in smart agriculture to another serving URLLC for autonomous vehicles.

- **Same vertical industries with different operators:** Handovers between slices serving the same industry but controlled by different operators as shown in Fig. 5.7(c) , such as in cross-border scenarios for connected vehicles or international smartphone roaming. It needs to ensure continuous service in applications where users or devices move across different operators' coverage areas but needs consistent service quality and features.



(a) Different vertical industries with different operators (b) Different vertical industries with same operators



(c) Same vertical industries with different operators

FIGURE 5.7: Types of Inter-slice handover.

5.3 Introduction to Radio Access Technology

RAT refers to the technology used by mobile devices to connect to a network. It encompasses various standards and protocols that enable communication between mobile devices and a network's base stations. RAT is crucial in determining mobile networks' performance, speed, and coverage. RAT encompasses a range of standards like WiFi, WiMAX (Worldwide Interoperability for Microwave Access), LTE, and now 5G NR. The choice of RAT directly impacts the user experience, network efficiency, and overall quality of service.

A comparison of key features and characteristics of four different wireless communication technologies: WiFi, WiMAX, 4G (LTE), and 5G as shown in Table 5.2. WiFi operates on IEEE 802.11 standards with a short coverage range, suitable for local area networking, while WiMAX operates over longer distances up to 30 miles. 4G (LTE) provides speeds of up to 100 Mbps and is deployed nationwide, whereas 5G offers ultra-low latency and speeds of several gigabits per second, supporting applications such as enhanced mobile broadband, IoT, and critical communication services. Each technology has specific deployment scenarios and use cases, catering to different connectivity needs across various contexts [77], [78]. The characteristics of RATs have affected the user's experience of service.

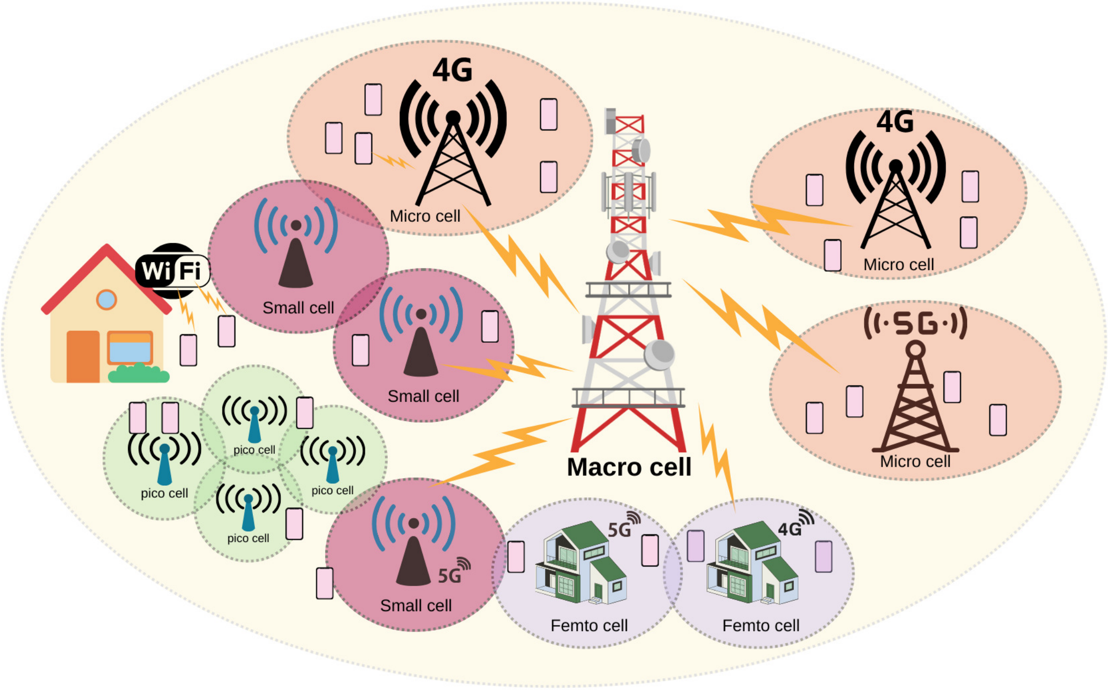


FIGURE 5.8: Heterogeneous Networks (HetNets).

RAT plays a pivotal role in Heterogeneous Networks (HetNets) by enabling the deployment of diverse base stations with different characteristics to optimize network performance, enhance coverage, and deliver seamless connectivity across various environments as shown in Fig. 5.8. The integration of multiple RATs in HetNets allows operators to address the evolving connectivity needs of users and leverage the full potential of wireless communication technologies.

HetNets offer numerous advantages, including improved coverage quality, enhanced performance for cell-edge UEs, boosted spectral and energy efficiency, as well as reduced operational and capital expenditures. However, they also pose several challenges such as determining the optimal base station selection for UEs and addressing the increased power consumption associated with extending network infrastructure [79].

TABLE 5.2: Comparison of WiFi, WiMAX, 4G, and 5G Technologies

Feature	**WiFi**	**WiMAX**	**4G (LTE)**	**5G**
Frequency Band	2.4 GHz, 5 GHz	2.3 GHz, 2.5 GHz	Multiple	Multiple
Coverage Range	Typically short range	Up to 30 miles	Up to 10 miles	Up to 1 mile (mmWave), several miles (Sub-6 GHz)
Technology	IEEE 802.11 standards	IEEE 802.16 standard	LTE Advanced	NR (New Radio)
Latency	Low	Low	Low	Ultra-low
Deployment	Local area networking	Metropolitan area networking	Nationwide deployment	Global deployment
Use Cases	Home and office networking, public hotspots	Fixed broadband access, last-mile connectivity	Mobile internet access, IoT, VoLTE	Enhanced mobile broadband, IoT, critical communication

5.3.1 WiFi

Wi-Fi, an abbreviation for Wireless Fidelity, is a technology that facilitates wireless internet connections for electronic devices or enables communication within a LAN. Utilizing radio frequencies facilitates data transmission between devices and access points, negating the necessity for wired connections [80]. WLAN has maintained steady growth in market share over the years, emerging as a crucial component in providing wireless data services through Wi-Fi technology. Its significance continues to rise, with home, enterprise, and hotspot environments increasingly reliant on Wi-Fi as their primary access network. This trend underscores the integral role of WLAN in facilitating seamless connectivity and enabling various digital services and applications across diverse settings.

The 802.11 Amendment marks a significant change in the way we refer to WiFi standards. It now uses two letters instead of one, which helps better categorize and understand standards like 802.11a, 802.11 b, 802.11 g, 802.11n, 802.11ac, 802.11ax (Wi-Fi 6) and 802.11be (Wi-Fi 7) as shown in Table 5.3. The IEEE 802.11 series presents distinct speed and range capabilities [81].

TABLE 5.3: Wi-Fi amendments.

Amendment	Year Released
IEEE 802.11b (Wi-Fi 1)	1999
IEEE 802.11a (Wi-Fi 2)	1999
IEEE 802.11g (Wi-Fi 3)	2003
IEEE 802.11e (QoS enhancements)	2005
IEEE 802.11n (Wi-Fi 4)	2009
IEEE 802.11ac (Wi-Fi 5)	2013
IEEE 802.11ah (Low-power WLAN and Extended range)	2017
IEEE 802.11ax (Wi-Fi 6)	2021
IEEE 802.11be (Wi-Fi 7)	2022

Recent standards like Wi-Fi 6 (The IEEE 802.11ax) deliver accelerated speeds, enhanced performance in congested surroundings, and heightened power efficiency compared to prior iterations. Wi-Fi 6 operates across the 2.4, 5, and 6 GHz frequency bands, resulting in high data rates reaching up to 9.6 Gb/s. The Wi-Fi 6 standard modifies both the PHY and MAC layers, introducing various features to enhance the WiFi user experience. These include wider channels, MU OFDMA for improved channel access, uplink (UL) MU MIMO to enhance capacity, SR for better spectral efficiency, Target Wake Time (TWT) for efficient power management, 1024 Quadrature Amplitude Modulation (QAM) to boost throughput, and other enhancements [82].

the latest version of the IEEE 802.11 standard is Wi-Fi 7 (IEEE 802.11be) [83], [84]. Wi-Fi 7 is expected to enhance the user experience in ultra-high-definition streaming, gaming, and virtual/augmented reality applications by developing as follows:

- **Speed:** Expected to offer maximum theoretical speeds exceeding 30 Gbps, significantly higher than Wi-Fi 6, making it the fastest Wi-Fi technology.

- **Technology:** Will introduce new features like 320 MHz channel bandwidth (compared to Wi-Fi 6's 160 MHz), higher-order QAM (4096-QAM), and Multi-Link Operation (MLO), which allows devices to transmit data across multiple frequency bands simultaneously for better performance and reliability.

- **Frequency Bands:** Besides 2.4 GHz and 5 GHz, Wi-Fi 7 is expected to operate in the 6 GHz band, providing more spectrum and reducing interference.

5.3.2 WiMAX

WiMAX, short for Worldwide Interoperability for Microwave Access, is a standardized technology overseen by the Institute of Electrical and Electronics Engineers (IEEE). Introduced in the early 2000s, IEEE established the IEEE 802.16 series of standards to define WiMAX, initially focusing on providing wireless MAN access. Among these standards, IEEE 802.16d, introduced in 2004, marked a significant milestone by offering practical applicability and laying the groundwork for WiMAX adoption [77]. This standard aimed to deliver high-throughput wireless data, providing last-mile broadband connectivity to fixed users. It emerged as a substantial competitor to DSL and cable data providers, offering an alternative solution for accessing high-speed internet services.

One of the key features of WiMAX networks is their capability to provide a high QoS and reliable communication across extensive transmission ranges. WiMAX is particularly recognized for its ability to maintain low packet loss ratios, enabling efficient management of both short packet durations and long-distance communication. This reliability contributes to its appeal in various applications requiring consistent and dependable connectivity [85].

WiMAX Release 2, slated for launch in late 2012, represents a second-generation advancement in high-speed wireless communication technology, building upon the foundation of the initial WiMAX release. This upgraded version offers accelerated upload and download speeds, reaching up to 90 Mbps and 170 Mbps, respectively, surpassing the capabilities of its predecessor. Additionally, WiMAX Release 2 is set to replace the existing IEEE 802.16e standard with the more advanced IEEE 802.16m, further enhancing its performance and functionality.

WiMAX and LTE, both emerging as contenders in the realm of wireless communication, began their rivalry with their pre-4G iterations and persisted through their 4G advancements, sharing many similarities along the way. Ultimately, it appears that WiMAX chose to relinquish the competitive stance and opt for harmonization and integration with LTE technology [86].

Chapter 6

Intelligent Algorithms

In this chapter are described Genetic Algorithms (GAs), Neural Networks (NNs) and Particle Swarm Optimization (PSO).

Intelligent algorithms are frequently applied to more difficult class combinatorial optimization problems. To solve optimization problems, intelligent algorithms can be used as an approximate solution. The approximate solution is a technical term used in contrast to the exact solution. The exact solution refers to an algorithm with an assurance of optimality, whereas the approximate solution is an algorithm without a guarantee of optimality. There is no guarantee in the intelligent algorithm of strict optimality, which is the similarity it shares with the approximate solution. The intelligent algorithm can obtain a good solution according to the calculation time at any time but the termination criterion of the approximate solution is not clear.

6.1 GA Description

The GA itself is an algorithm that simulates the process of evolution of living things introduced by Holland [87] in the 1960s. The GAs are Evolution Computation (EC) techniques which search for optimal solution to a problem. These algorithms encode a potential solution to a specific problem on a simple chromosome-like data structure and apply recombination operators to these structures to preserve critical information.

In every generation, a new set of chromosome is recreated using parts of the fittest members from the old set. When the results become the target goal, the process will be finished. These algorithms evolve the generation using following operators: Selection Operator, Crossover Operator and Mutation Operator. GAs are often viewed as function optimizer which generate high-quality solution for optimization problem and search [88] .

As shown in Fig. 6.1 and Fig. 6.2, GAs start with creating an initial population from generating population randomly or seeded by other heuristics. This population can be like a collection of chromosomes. Then, it evaluates fitness for each of each

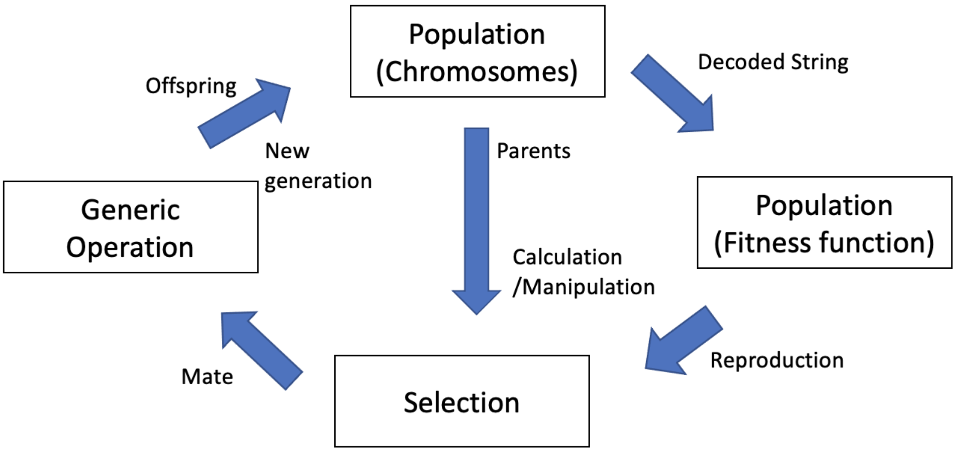


FIGURE 6.1: GA cycle.

chromosome in the population and selects parents from this population for mating. After that, it uses crossover and mutation operators on the parents for generating a new population. Finally, it creates a new population by repeating the previous steps (selection, crossover, mutaion, replace, test) until the new population can be satisfied in the end condition. Then, the loop will end. The GA loops are repetition processes to make the population evolve and finding the best result. Each repetition processing includes four steps as follow.

- **Selection:** The step includes selecting individuals for reproduction and is made randomly with a probability depending on the relative fitness of the individuals. Because of that, the selection will often choose the best ones than bad ones.

- **Reproduction:** In the second step, the selected individuals make offspring to breed. The algorithm can use both recombination and mutation for generating new chromosomes.

- **Evaluation:** In the third step, the fitness of the new chromosomes is evaluated.

- **Replacement:** During the final step, individuals from the old population are replaced by the new ones.

Advantages and Limitations of GAs

The GA is a stochastic and parallel optimization algorithm which can discover easily the global optimum. Also, it can be modified for different problems and can solve the problem which has multi-objective function. Moreover, it can be implemented very well for a wide variety of optimization problems. But, GA has problems with identifying fitness function and choosing the various parameters such cross over rate, size of the population and mutation rate. It cannot use gradients and incorporate

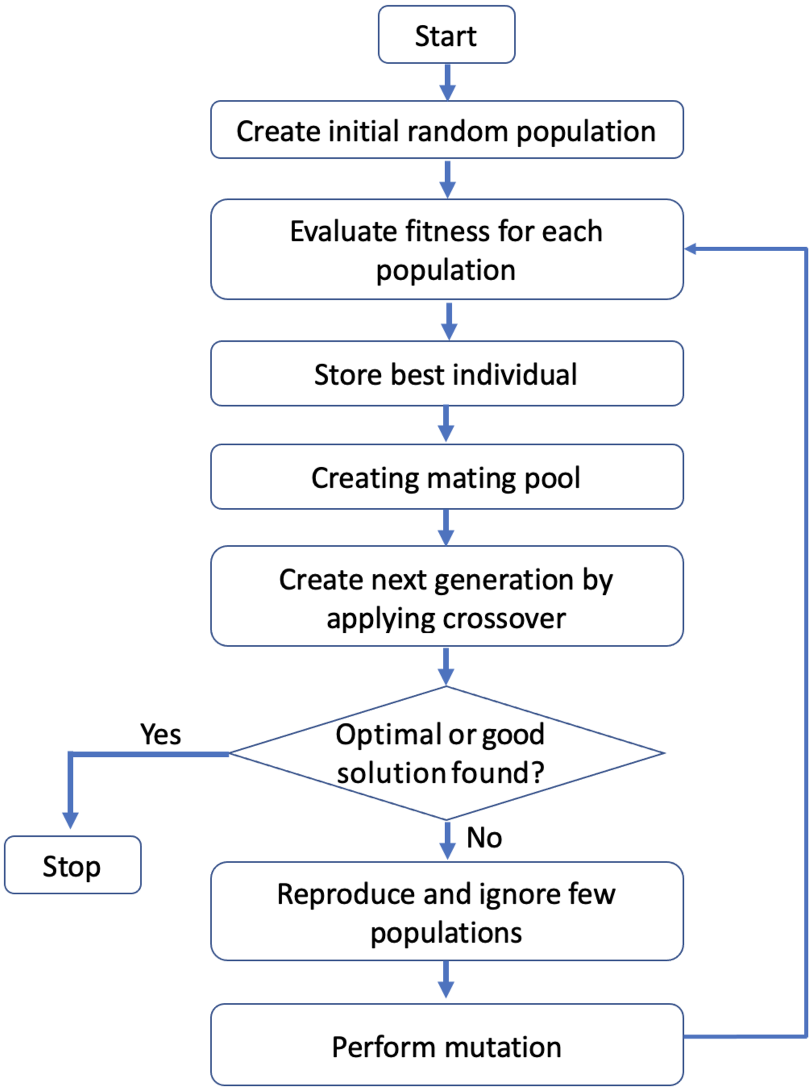


FIGURE 6.2: GAs flowchart.

problem-specific information. Moreover, it needs to be coupled with a local search technique.

Applications of GAs

The GAs has been applied to solve complex problems for improving the system and machine learning for optimization problems of various kinds. A few applications of GA are as follows:

- Machine Learning–Designing neural networks, both architecture and weights, improving classification algorithms, classifier systems;
- Image Processing;
- DNA Analysis;

- Multimodal Optimization;
- Strategy planning;
- Sequence scheduling.

6.2 NNs Description

There are different kind of NNs such as Artificial Neural Networks (ANN), Recurrent Neural Networks (RNN) and Convolutional Neural Network(CNN).

6.2.1 Artificial Neural Networks (ANN)

The ANN is a Feed-Forward NN which is designed to simulate based on human brain analyzes or statistical standards for solving problems. In Fig. 6.3, ANN is represented graphically as a set of neurons connected together, in which the information flows only in the forward direction, from inputs to outputs. It consists of three layers. The first layer is the input layer, which receives data from many sources such as data files, images, hardware sensors and microphones. The second layer is the hidden layers that process the data by mathematical functions, which are designed to produce a specific output for an intended result. For example, some forms of hidden layers are known as squashing functions. The third layer is the output layer, which provides one or more data points based on the function of the network and produces the final result.

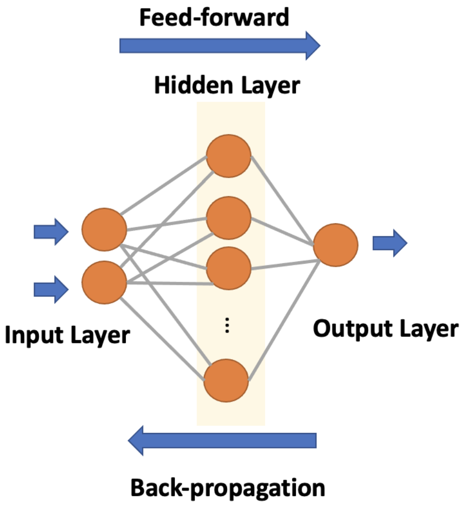


FIGURE 6.3: ANN architecture.

6.2.2 Recurrent Neural Networks (RNN)

Comparing with ANN, the RNN has "memory," which is information from previous inputs within the sequence to affect the current input and output as shown in Fig. 6.4. The RNN can handle sequential data accepting the current input data and previously received inputs. So, it is often used for ordinary or temporal problems, such as language translation, Natural Language Processing (NLP), speech recognition and image captioning.

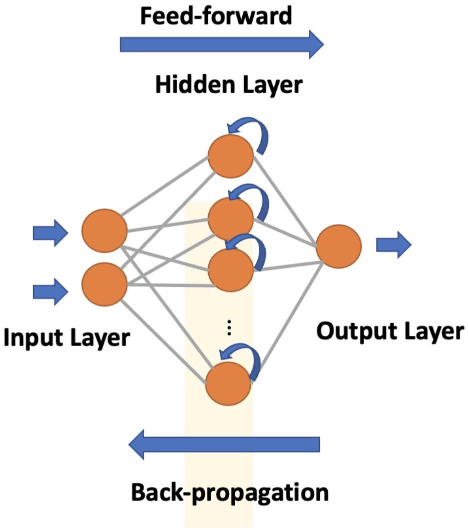


FIGURE 6.4: RNN architecture.

6.2.3 Convolutional Neural Network (CNN)

The CNN makes an image as an input and creates weight and biases into the object in the image and can detect remarked one from the others. A CNN leverages the fact that an image consists of more minor details or features and creates a mechanism for analyzing each feature in isolation, which informs a decision about the image as a whole.

The learning method in CNN uses the backpropagation model. For updating the weighting filter and coupling coefficient, CNN recognizes the optimized feature and analyzes it by using the convolutional and pooling operations. The feature maps of the last convolutional layer are vectorized and fed into fully connected layers for category recognition, followed by a softmax logistic regression layer. Rectified Linear Units (ReLU) will be used to speed up training. Figure 6.5 illustrates the CNN architectures [89].

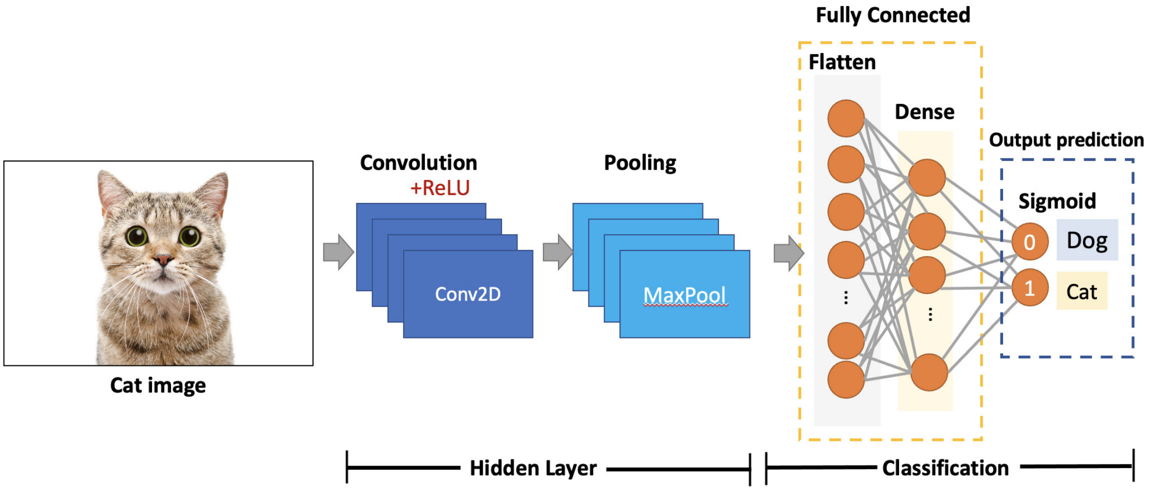


FIGURE 6.5: CNN architecture.

Advantages and Limitations of NNs

The NN is a learning algorithm that has the ability to learn by itself and no limit to provide input for generating output. Furthermore, if data loss happens in the database, it has no effect on the NN because it can store data in its network. But it also has some disadvantages. The NN is more complicated than traditional algorithms in computing terms and has black-box nature that makes it difficult to show the problem in the network.

Applications of NNs

The NN can be used to solve many complicated problems and be implemented in many applications such as face recognition, real-time AI translation and falt-detection. Also, it has only recently come under AI due to some applications that makes it more preferable. The applications include:

- Image processing;
- Language processing and translation;
- Speech recognition;
- Forecasting.

6.3 Particle Swarm Optimization (PSO)

The PSO is an intelligent algorithm developed by J. Kennedy and R. Eberhart in 1995 through the simulation of a simplified social model [90]. The PSO is a swarm intelligence-based numerical optimization algorithm inspired by birds' flocking or fish schooling for the solution of nonlinear, nonconvex, or combinatorial optimization problems [91]. In PSO, the solution is obtained by a random search which is done by a set of randomly generated potential solutions.

Each potential solution is called a particle and the collection of potential solutions is called a swarm. The particle will move to the search domain for searching optimal solutions by a specified velocity and keeps track of its previous best position. Comparing with its previous best position, it will choose the best position for the solution. Fig. 6.6 is showing the flowchart of PSO.

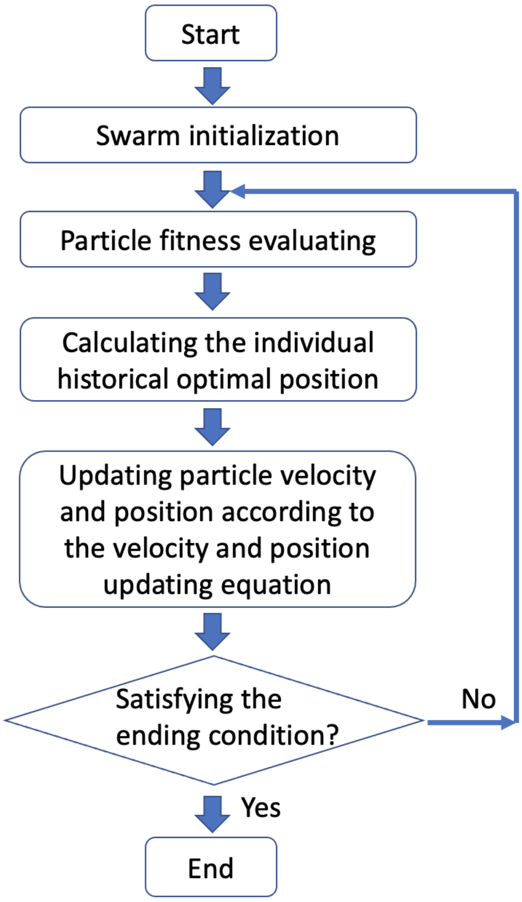


FIGURE 6.6: PSO flowchart.

The changed position of the particle ($x_i(t+1)$) can be calculated and written as following formula:

$$x_i(t+1) = x_i(t) + v_i(t)$$

where, *xi(t)* is the position of particle *(i)* in the search space at time step *(t)*, *vi(t)* is a velocity of particle *(i)* at time step *(t)* and t is discrete time steps. The velocity of particle makes the optimal process by considering the experiential knowledge and exchanged social information from the particle's neighborhood. The experiential knowledge of a particle is considered as the cognitive component and the exchanged social information is considered as the social component of the velocity equation.

PSO algorithms is divided into two types by different of their neighborhoods's size, known as global best PSO (gbest PSO) and local best PSO (lbestPSO). In the following we explain how these two types of algorithms find the solution to a given problem [92].

Global Best PSO (gbest PSO)

The global best PSO or gbest PSO applies the star topology in the employed social network and makes the entire swarm be the neighborhood for each particle. At each iteration, the particles explore the search space for solutions. The information obtained is used in the following iteration to update the velocities of each particle. The velocity of a particle in each iteration is updated using three components. The first component is the velocity of the particle in the previous iteration. The second is the cognitive component which is the best solution that the particle itself has found so far while exploring the search space. The other component is the social component which refers to the information obtained by the other particles, that is, the best solution found until this point of the simulation.

Local Best PSO (lbest PSO)

The local best PSO, or lbest PSO, applies the ring topology in the employed social network and defines small neighborhoods for each particle instead of using the entire swarm as the neighborhood. The updated velocity of the particle has the same components as in the gbest PSO, but here the obtained information from the other particles, the social component, is not the same. Since the neighborhood of the particle is not the entire swarm but a smaller number of particles, the social component in lbest PSO refers to the best solution found by only those particles that comprise the neighborhood of the particle. This enables the algorithm to search for solutions in larger parts of the search space, reducing the chances of being stuck in local minima, but, on the other hand, increases the time that is required for the algorithm to converge to the solution.

Advantages and Limitations of PSO

The PSO can use few parameters to adjust the system and it can be implemented easily and simply without requiring the differential of the optimized function, derivative and continuous. Moreover, it can converge fast and have a short computation time. Therefore, PSO can be an efficient algorithm for solving problems that are hard to find accurate mathematical models. But, it also has some disadvantages. In PSO is hard to define designed parameters in the initial step and can be trapped into a complex problem. It is not suitable for the problems of scattering.

Applications of PSO

The PSO has been applied to solve a variety of optimization problems [93]. Various areas where PSO is applied are as follows.

- Antennas Design such as the optimal control and design of phased arrays, broadband antenna design and modeling.
- Signal Processing such as Pattern recognition of flatness signal, design of Infinite Impulse Response (IIR) filters.
- Electronics and electromagnetic such as AC transmission system control, electromagnetic shape design, microwave filters, generic electromagnetic design and optimization applications.
- Robotics such as control of robotic manipulators and arms, motion planning and control.

Chapter 7

Fuzzy Logic

In this chapter is presented outline of FL, operation of a Fuzzy Logic Controller (FLC), the Defuzzification methods and Linguistic Variables.

7.1 Outline of Fuzzy Logic

A Fuzzy Logic (FL) system is a nonlinear mapping of an input data vector into a scalar output, which is able to simultaneously handle numerical data and linguistic knowledge. Boolean logic can deal with statements that may be true, false but the FL can deal with more than that statement. It also can deal with intermediate truth-value. For example, if we use boolean logic to answer a question like "Is it cold?", boolean logic can only with two answers are yes or no but the FL can answer more than two answers as shown in Fig. 7.1. Also, those statements are impossible to quantify using traditional mathematics. The FL system is used in many controlling applications such as aircraft control (Rockwell Corp.), Sendai subway operation (Hitachi), and TV picture adjustment (Sony) [94]–[96].

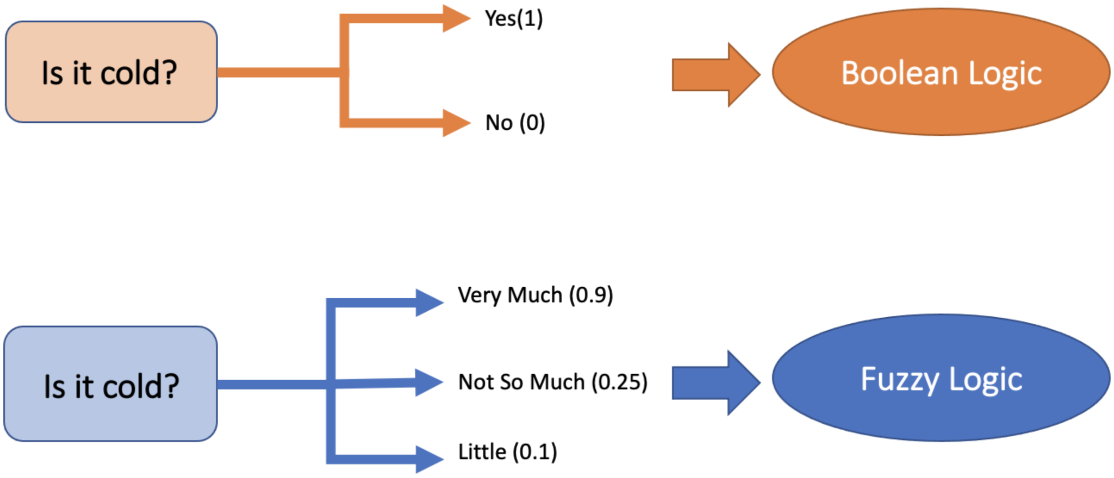


FIGURE 7.1: Boolean logic and FL.

7.1.1 Operation of a Fuzzy Logic Controller

In Fig. 7.2 is shown FLC structure, which contains four components: fuzzifier, inference engine, fuzzy rule base and defuzzifier.

- **Fuzzifier** is needed for combining the crisp values with rules which are linguistic variables and have fuzzy sets associated with them.
- **The Rules** may be provided by on expert or can be extracted from numerical data. In engineering case, the rules are expressed as a collection of IF-THEN statements.
- **The Inference Engine** infers fuzzy output by considering fuzzified input values and fuzzy rules.
- **The Defuzzifier** maps output set into crisp numbers.

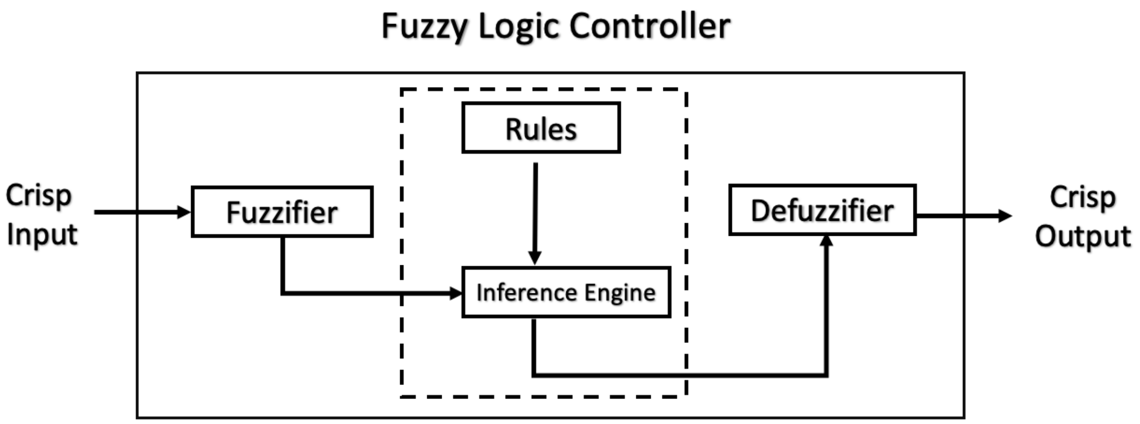


FIGURE 7.2: FLC structure.

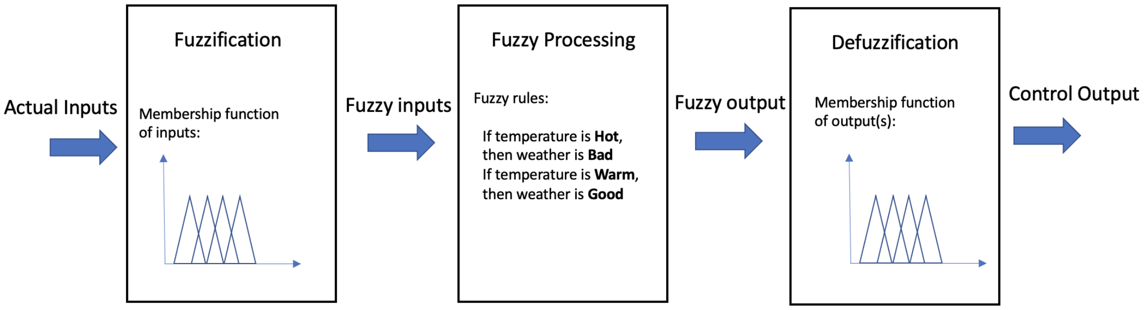


FIGURE 7.3: Operation of a fuzzy controller.

In Fig. 7.3 is shown the operation of the fuzzy controller. In the first step, by the Fuzzifier are fuzzified the actual inputs to obtain fuzzy inputs. Then, Inference Engine will process fuzzy inputs according to the rules set and produces fuzzy outputs. Finally, the Defuzzification produces a crisp real value from fuzzified inputs for control output.

7.1.2 Fuzzification

Fuzzification is the process of converting crisp sets to a fuzzy set.

Fuzzy Sets

A fuzzy set is part of the classical set, a set without a crisp, clearly defined boundary and can contain elements with only a partial degree of membership between 1 and 0. For example, the number of cars following traffic signals at a particular time out of all cars present will have a membership value between [0,1].

Membership Function

The membership function defines how to map each point in the crisp inputs with a degree of membership between 0 and 1 to create a graph. It can characterize fuzziness to represent the degree of truth in fuzzy logic as shown in Fig. 7.4. Usually, more than one membership function can be used to describe a single input variable. For example, a three-level fuzzy system with fuzzy sets 'Low', 'Medium' and 'High' is applicable to represent a single input variable.

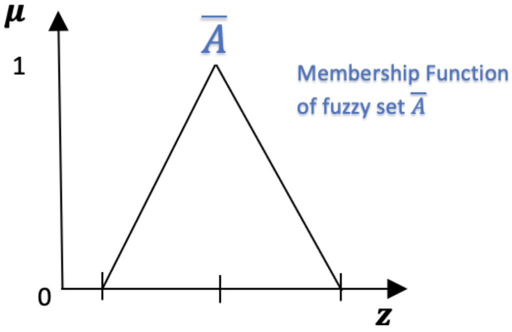


FIGURE 7.4: Membership Function.

In Fig. 7.5, the features of the membership function consist of three component.

- **The Core** is the region of universe which have the membership function as 1 and can be written as $\mu_A(z) = 1$.
- **The Support** is the region of universe characterized by nonzero membership and has the elements whose membership is greater than zero. This can be written as $\mu_A(z) > 0$.
- **The Boundary** is the region of universe when memberships values are between 0 and 1. This can be written as $0 < \mu_A(z) < 1$.

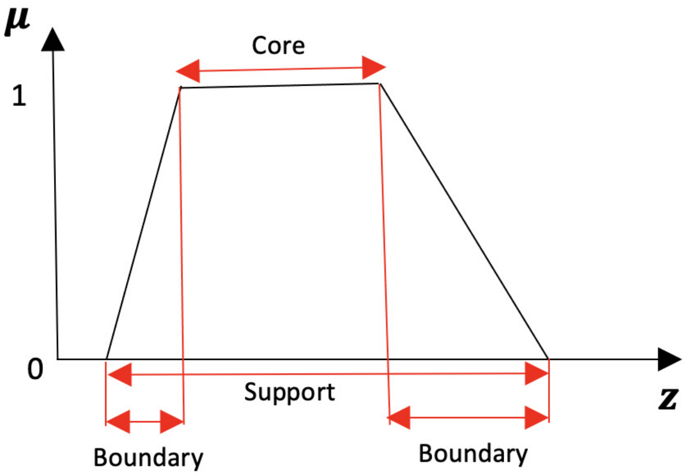


FIGURE 7.5: Features of membership function.

7.1.3 Fuzzy Processing

Fuzzy Inference Process

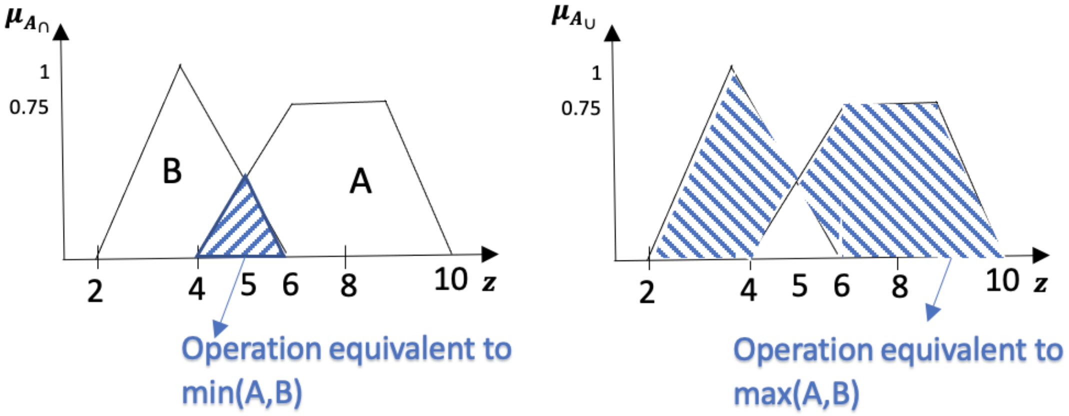
Fuzzy inference formulates the mapping from a given input to an output using FL. The mapping then provides a basis from which decisions can be made or patterns discerned. It involves membership functions, fuzzy logic operators and if-then rules. The first process of Fuzzy Inference fuzzifies the crisp values of input variables into membership values according to appropriate fuzzy sets. In the second process, the results of all rules are integrated into a single precise value for output. Two main types of fuzzy inference systems can be implemented for fuzzy systems based on linguistic rules: Mamdani Fuzzy Inference and Sugeno Fuzzy Inference.

- **Mamdani Fuzzy Inference:** In Mamdani Fuzzy Inference, the output membership functions are fuzzy sets that need defuzzification for making the output of FLC. A fuzzy set defines the consequence of the If-Then rule. The rules can be created from human expert knowledge and experience in Mamdani Fuzzy Inference. So, its rules base has more intuitive and easier to understand rule bases. Also, a matching number will reshape the output fuzzy set of each rule and defuzzification is required after aggregating all of these reshaped fuzzy sets.

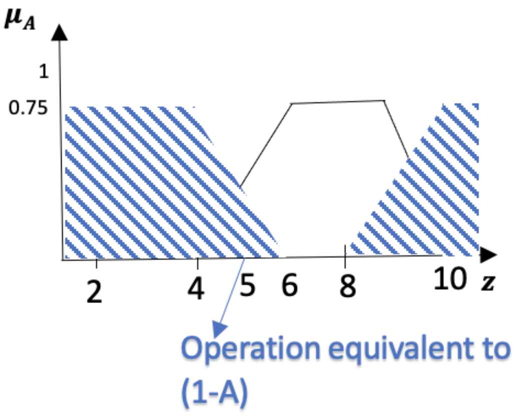
- **Sugeno Fuzzy Inference:** In Sugeno Fuzzy Inference, the consequence of the If-Then rule is explained by a polynomial with considering input variables. The output of each rule is a single number. It uses a weighting mechanism for the final crisp output. Sugeno Fuzzy Inference can avoid complex defuzzification but comparing with Mamdani Fuzzy inference the work of determining the parameters of polynomials is inefficient and less straightforward than Mamdani Fuzzy inference.

Logical Operations

In FLC, the truth of any statement is a matter of degree. The input values can be real numbers between 0 and 1. Any construction can be resolved using fuzzy sets and the fuzzy logical operations AND, OR, and NOT. To extend to all real numbers between 0 and 1, the results of the statement A AND B, which uses min (A, B) to resolve A and B, are limited in the range (0, 1). Moreover, A OR B becomes equivalent to max (A, B) by replacing OR operation with the max function, and the operation NOT A becomes equivalent to operation 1-A. An example of the operations on fuzzy sets is shown in Fig. 7.6.



(a) Operation equivalent to min(A,B) (b) Operation equivalent to max(A,B)



(c) Operation equivalent to (1-A)

FIGURE 7.6: Operations on fuzzy sets.

Fuzzy Control Rules

Fuzzy control rules are usually written in the form "IF x is S THEN y is T" where x and y are linguistic variables that are expressed by S and T, which are fuzzy sets. The x is the control (input) variable and y is the solution (output) variable. This rule is called Fuzzy control rule. The form " IF ... THEN " is called a conditional sentence. It consists of " IF " which is called the antecedent and " THEN " is called the consequent.

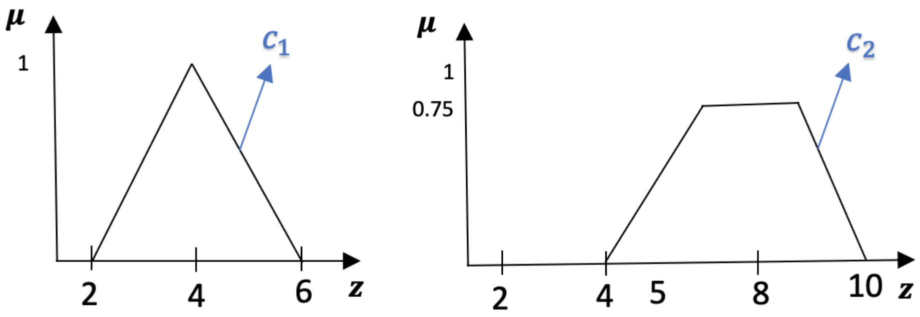
TABLE 7.1: The canonical form for a fuzzy rule-based system.

Rule 1:	IF condition C^1, THEN restriction R^1
Rule 2:	IF condition C^2, THEN restriction R^2
.	.
.	.
.	.
Rule r:	IF condition C^r, THEN restriction R^r

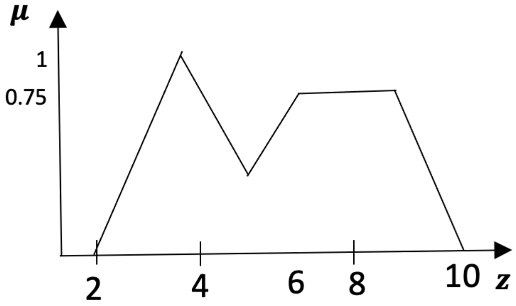
In Table 7.1 are showing several simple canonical rules from decomposing and reducing any compound rule structure. These rules are based on natural language representations and models, which are represented based on fuzzy sets and FL. The fuzzy level of understanding and describing a complex system is expressed from the form of a set of restrictions on the output with the condition of the input $(C_1, C_2, .., C_r)$. These condition statements are usually connected by linguistic connectives such as "and," "or," or "else." The restrictions $R_1, R_2, ..., R_r$ apply to the output actions or consequents of the rules.

7.1.4 Defuzzification

Defuzzification converts fuzzified quantity to a precise quantity (crisp value) with respect to a fuzzy set. The output of defuzzification can be the logical union of more than two fuzzy membership functions. For example, a fuzzy output consist of two-part: C_1 (triangular shape) and C_2 (trapezoidal shape). The logical union of C1 and C2 is $C_{output} = C_1 \cup C_2$ with the max operator. The result of that operation is graphically shown in Fig. 7.7. The membership function representing each part of output can be other shapes more than these two shapes.



(a) First membership function (b) Second membership function



(c) Defuzzification step

FIGURE 7.7: Typical fuzzy output.

The Centroid Method

The Centroid or Center of Gravity (CoG) defuzzification method stands as the predominant technique in fuzzy logic applications, providing a precise output value. This method calculates this value by determining the center of gravity of the area under the curve of the fuzzy set along the x-axis. It integrates across the shape of the fuzzy set to find a balance point, akin to finding the balance point of a physical object. This approach ensures that the resultant crisp value is representative of the entire fuzzy set, offering a balanced and accurate conversion from fuzzy data to a specific numerical outcome. In Fig. 7.8, the centroid defuzzification technique is computed using the following formula:

$$z_{CoG} = \int \frac{\mu_z z dz}{\mu_z dz}$$

where z_{CoG} is the crisp output, μ_z (z) membership function is the aggregated membership function and z is the output variable. In [97], they use this method for measuring velocity and magnetic field strength in the solar photoshere.The CoG method can proves to be dependable for gauging velocities within the lower segment of these formation heights and for assessing field strength across the entire spectrum of heights without affecting by spectral resolution.

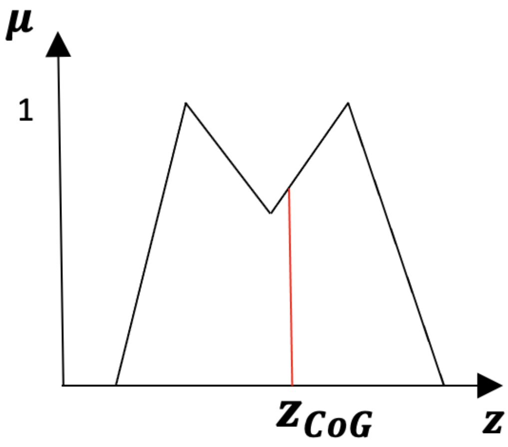


FIGURE 7.8: COG method.

Weighted Average Method

The Weighted Average Method is one of the more computationally efficient methods but it is restricted to symmetrical output membership functions. This method is less computationally intensive. Each membership function is weighted by its maximum membership value. This method is computed using the following formula:

$$z^* = \frac{\sum \mu_C(\bar{z})\bar{z}}{\sum \mu_C \bar{z}}$$

where z^* is the crisp output, the symbol $\bar{z}$ is the centroid of each symmetric membership function and $\sum$ denoted the algebraic sum. Fig. 7.9 shown that the weighted average method is formed by weighting each membership function in the output by its largest membership value.

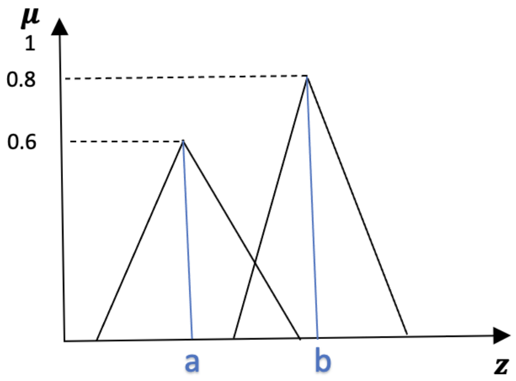


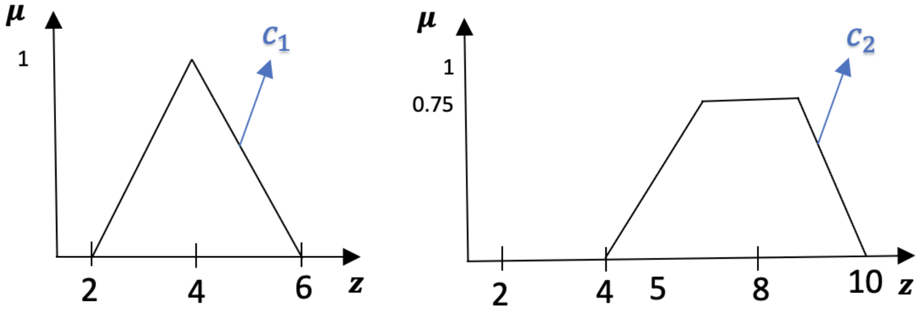
FIGURE 7.9: The Weighted Average method.

Center of Sums Method (CoS)

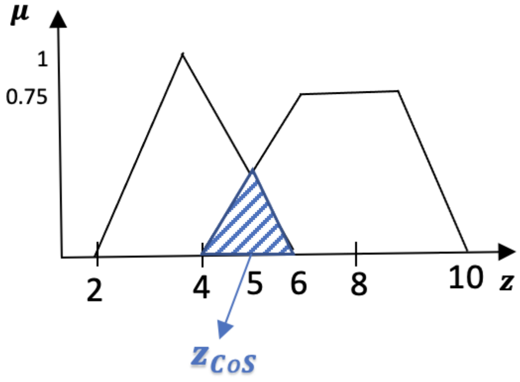
The Center of Sums (CoS) defuzzification technique is the most commonly used defuzzification technique and is faster than other defuzzification methods. It is not restricted to symmetric membership function. In Fig. 7.10, this method involves the algebraic sum of individual output fuzzy sets like C_1 and C_2, instead of their union and its defuzzification considering the intersecting area is counted twice. This method is computed using the following formula:

$$z_{COS} = \frac{\sum_{k=1}^{n} \mu_{C_k} \int_z \bar{z} dz}{\sum_{k=1}^{n} \mu_{C_k} \int_z dz}$$

wheres z_{COG} is the crisp output, the symbol $\bar{z}$ is the distance to the centroid of each of the respective membership functions.



(a) First membership function (b) Second membership function



(c) Defuzzification step

FIGURE 7.10: CoS method.

Center of Largest Area (CoA) Method

The Center of largest Area (CoA) method divides the fuzzy set into two sub-regions of equal area and calculates the position under the curve where the areas on both sides are equal. Then, the entirety of gravity of the convex sub-region with the largest area can be used to calculate the defuzzification value as shown in Fig. 7.11. This method is computed using the following formula:

$$z_{COA} = \frac{\int \mu_{C_m}(z) z dz}{\int \mu_{C_m}(z) dz}$$

where z_{CoA} is the crisp output which is same as the value z_{CoG} obtained by centroid method. This can be done even for non-convex regions. The symbol C_m is the convex region with largest area.

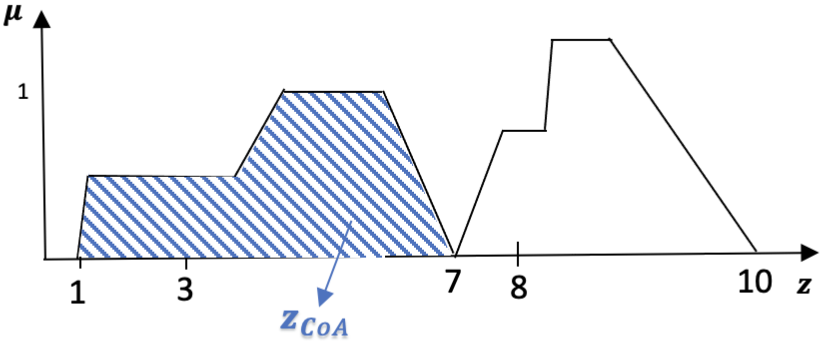


FIGURE 7.11: CoA method.

Maxima Methods

The Maxima Methods considers fuzzied values with maximum membership. It is divided to three types with different conflict resolution strategies for multiple maxima.

- **First of Maxima Method (FoM):** It uses the overall output to determine the domain's smallest value with maximized membership degree.
- **Last of Maxima Method (LoM):** Comparing with FoM, LoM determines domain's largest value with maximum membership degree as shown in Fig. 7.12.

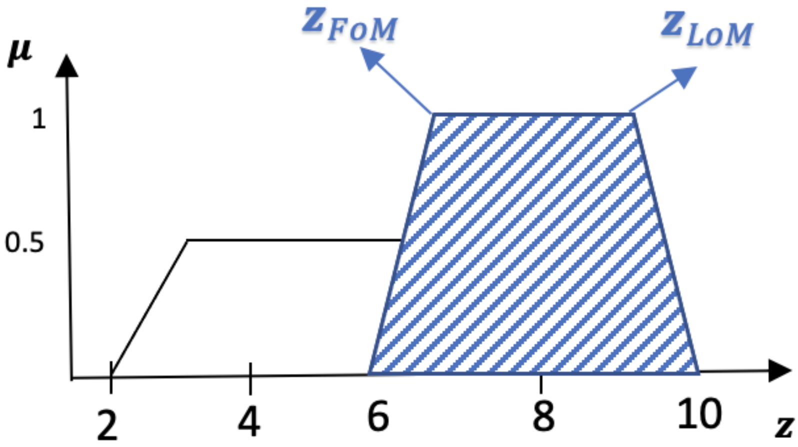


FIGURE 7.12: FoM and LoM.

- **Mean of Maxima Method (MoM):** MoM takes the defuzzified value as the element with the highest membership values. It is closely related to the FoM, except that the locations of the maximum membership can be nonunique. This method is computed using the following formula:

$$z_{MoM} = \frac{a+b}{2}$$

where z_{MoM} is the crisp output, a and b are defined in Fig. 7.13.

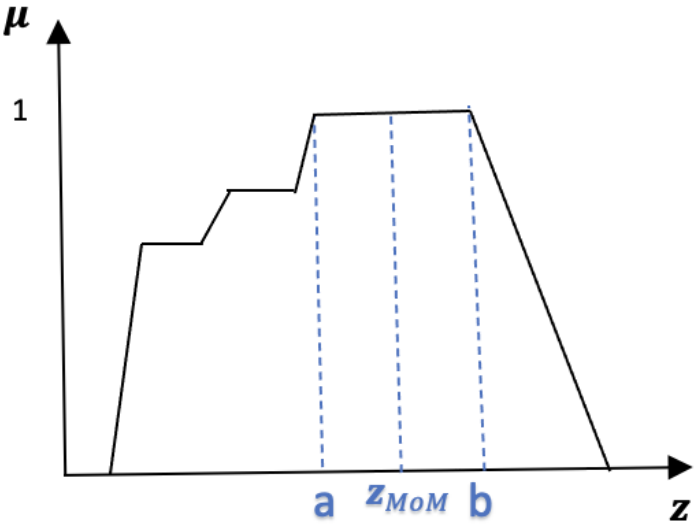


FIGURE 7.13: MoM.

7.2 Linguistic Variables

A concept that plays a central role in the application of FL is that of a linguistic variable. The linguistic variables may be viewed as a form of data compression. One linguistic variable may represent many numerical variables. We can classify the students of a class, by the score the got on the exam, by only four linguistic variables: Bad, Passed, Good and Exellent, out of 100 numerical variables (points) in total. It is suggestive to refer to this form of data compression as granulation.

The same effect can be achieved by conventional quantization, but in the case of quantization, the values are intervals, whereas in the case of granulation the values are overlapping fuzzy sets. The advantages of granulation over quantization are as follows:

- it is more general;
- it mimics the way in which humans interpret linguistic values;
- the transition from one linguistic value to a contiguous linguistic value is gradual rather than abrupt, resulting in continuity and robustness.

For example, let Temperature (T) be interpreted as a linguistic variable. It can be decomposed into a set of Terms: T (Temperature) = {Freezing, Cold, Warm, Hot, Blazing}. Each term is characterised by fuzzy sets which can be interpreted, for instance, “ freezing " as a temperature below $0°C$, “ Cold " as a temperature close to $10°C$.

Chapter 8

Proposed Intelligent System and Testbed Implementation

In this chapter are described the proposed system overview and the proposed system structure considering different input parameters.

8.1 Proposed Architecture

We use FL to implement the proposed system. In Fig. 8.1 and Fig. 8.2, we show the proposed system and its flowchart. The SDN controller will communicates with each eBS, which communicate and transfer data to UE. Also, each eBS can cover many slices.

The proposed integrated Fuzzy-based system will be implemented in SDN controller and has three modules: Fuzzy-based RATs Selection Module (FRSM), Fuzzy-based Admission Control Module (FACM) and Fuzzy-based Handover Module (FHM). The FRSM controls eBS and other RAT's base stations and collect, identifies and analyzies all data regarding network traffic situation. The SDN controller will act as a transmission medium between the RAT's base station and the core network. For example, when the UE is connected to WLAN but its QoS is not good, the SDN controller will collect other RAT networks data and decides whether the UE will still be connected with WLAN or connect to other RATs.

After selection of RAT, FACM will decide whether to accept or reject a new connection request from users based on that RAT's slice or eBS. If a new user will be rejected, a new user have to find another slice or eBS for sending a new connection request again. Otherwise, when a new user is accepted, the connection will be established. But, when QoS is not good or the user has moved to other place, FHM will carry out inter-eBS handover and inter-slice handover.

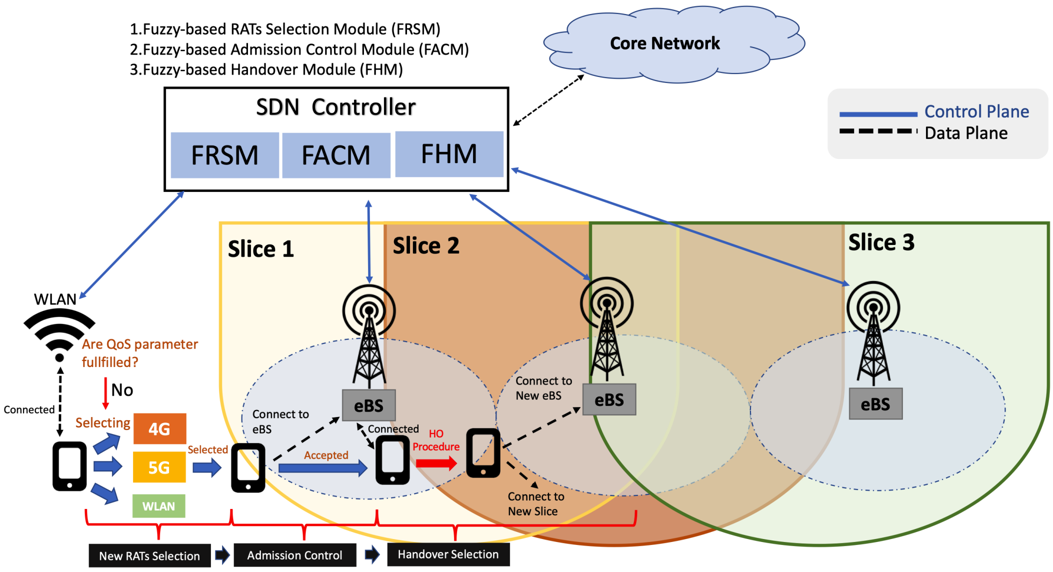


FIGURE 8.1: Proposed system architecture.

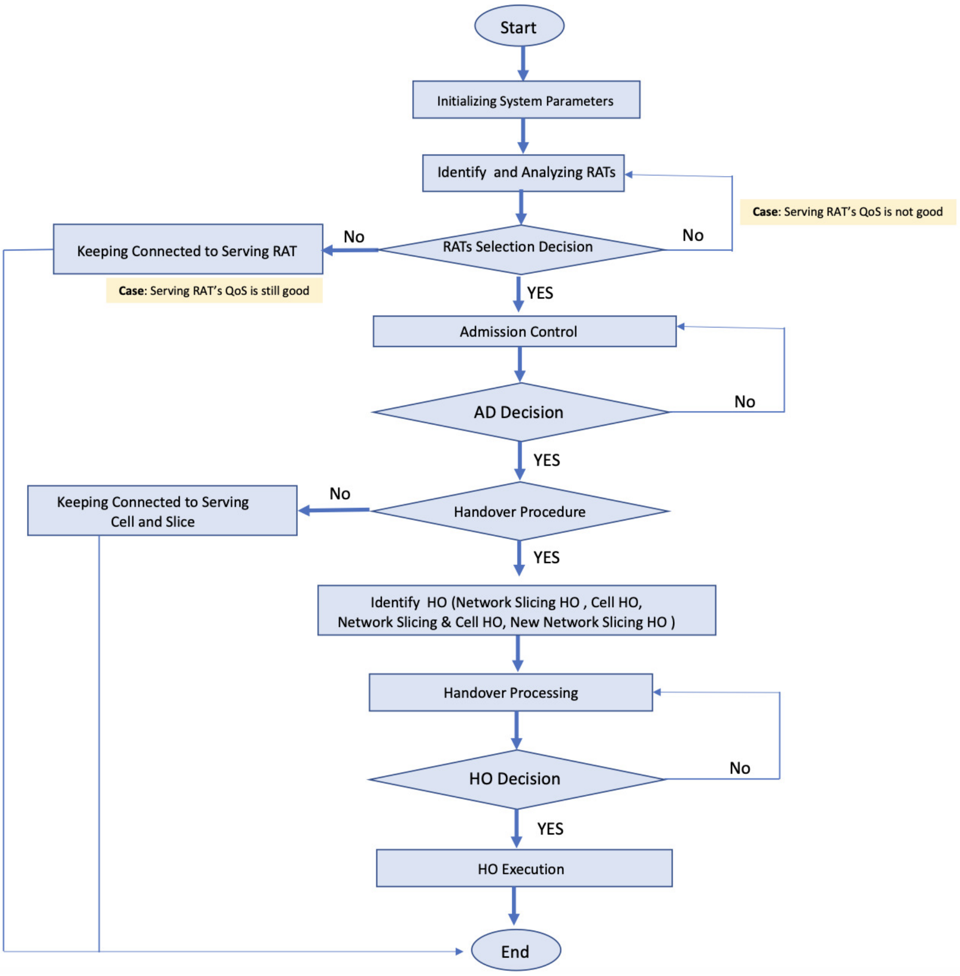


FIGURE 8.2: Proposed system flowchart.

8.2 Fuzzy-based RATs Selection Module (FRSM)

The 5G heterogeneous networks are anticipated to deliver a dense array of network services and diverse networking options to meet user needs. These networks are also designed to empower UE to seamlessly connect to the most suitable RAT. Yet, determining the optimal RAT involves considering a multitude of factors, making the selection process inherently complex and computationally challenging. To address this, we introduce a FRSM.

8.2.1 Structure of FRSM1 Considering CV, UP and SE

The FRSM1 evaluates three key parameters: Coverage (CV), User Priority (UP) and Spectral Efficiency (SE). The structures of FRSM1 is shown in Fig. 8.3. In following, we explain the input and output parameters of the FRSM1.

Coverage (CV): The CV parameter indicates the radius of each RAT cell. This value is decided based on factors such as signal strength and RAT-specific signal quality metrics.

- **5G** utilizes a combination of high, middle and low frequency bands for coverage and capacity. The range varies depending on frequency.
- **4G** offers a good coverage and range, especially in low frequency bands.
- **Wi-Fi** provides coverage within a limited area, usually a few hundred feet, making it suitable for indoor use.

User Priority (UP): The UP shows the priority of users or devices. When the UP is higher, the system will find a RAT that provide good QoS.

Spectral Efficiency (SE): The SE indicates the number of bits that can be transmitted using the existing transmission bandwidth, measured in bits per second per Hertz (bps/Hz). The SE indicates the data rate achievable within a specific bandwidth allocation, reflecting the efficiency of spectrum utilization. The formula for calculating SE can be expressed as follows:

$$SE = \frac{ADR(bps)}{AB(Hz)},$$

where, the ADR is Achievable Data Rate, which depends on the modulation scheme used, the number of bits transmitted per symbol, and other factors. The Available Bandwidth (AB) is the range of frequencies allocated for transmission.

RAT Decision Value (RDV): The RDV parameter is the output parameter, derived by proposed system and testbed by considering three input parameters. By evaluating and combining these input parameters, the RDV offers a quantifiable

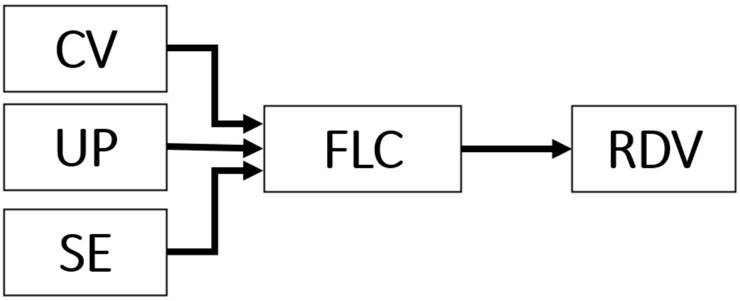


FIGURE 8.3: Proposed system structures for FRSM1.

measure that guides the selection of an optimal radio access technology, based on the specific conditions, requirements, and priorities.

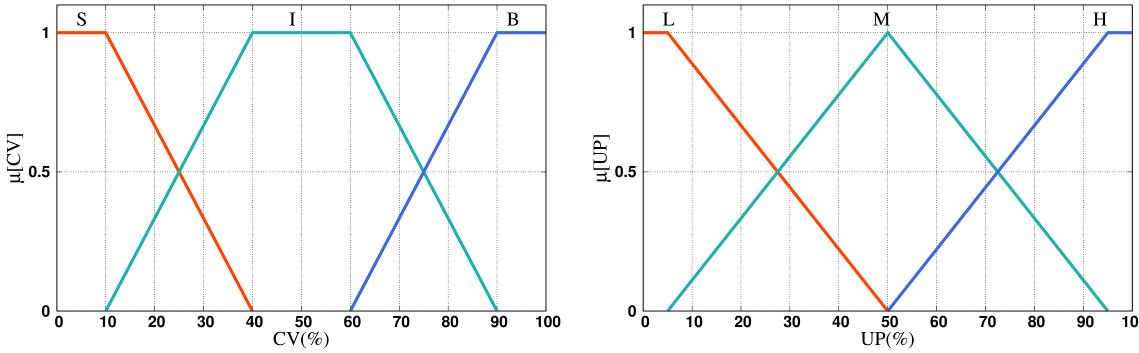
Table 8.1 shows Fuzzy Rule Base (FRB), which comprises of 27 rules. The membership functions are shown in Fig. 8.4. We select triangular and trapezoidal membership functions because they are well-suited for real-time operations and they can efficiently handle dynamic and time-sensitive processes [20], [98]–[100].

We explain the design of FLC in following. The input parameters and their term sets are as follows.

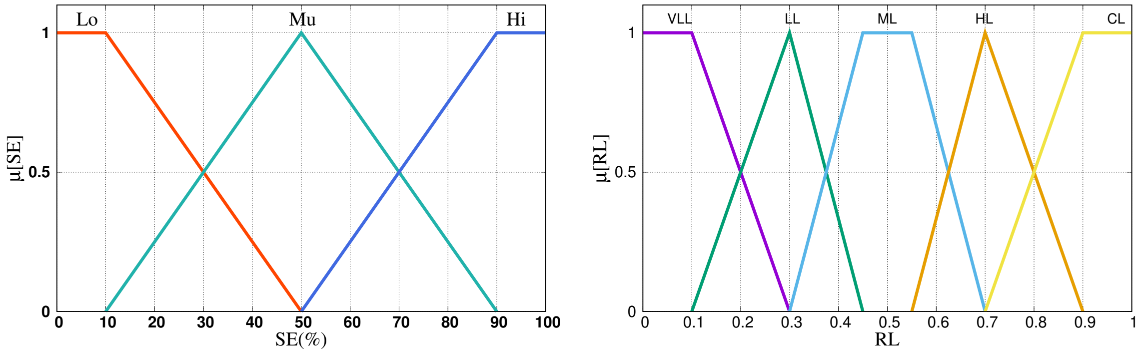
$$\begin{aligned} T(CV) &= \{Small\ (S), Intermediate\ (I), Big\ (B)\} \\ T(UP) &= \{Low\ (L), Medium\ (M), High\ (H)\} \\ T(SE) &= \{Low\ (Lo), Medium\ (Mu), High\ (Hi)\} \end{aligned}$$

The membership function for input parameters are defined as follows.

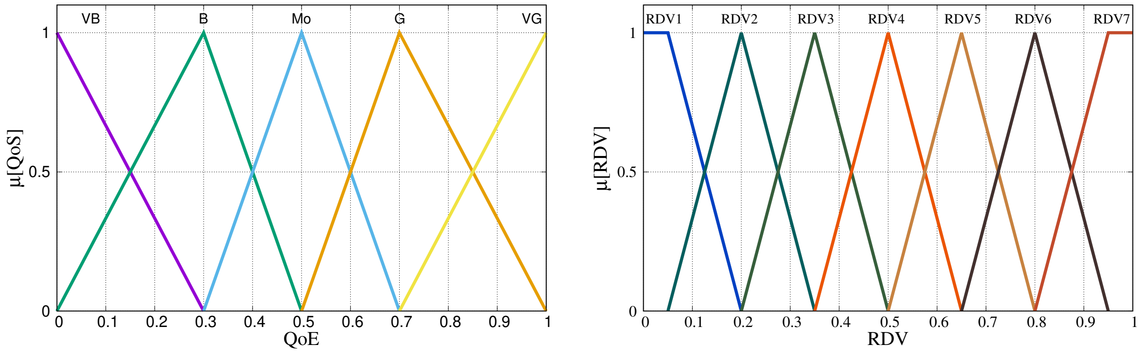
$$\begin{aligned} \mu_S(CV) &= g(CV; S_0, S_1, S_{w0}, S_{w1}) \\ \mu_I(CV) &= f(CV; I_0, I_1, I_{w0}, I_{w1}) \\ \mu_B(CV) &= g(CV; B_0, B_1, B_{w0}, B_{w1}) \\ \mu_L(UP) &= g(UP; L_0, L_1, L_{w0}, L_{w1}) \\ \mu_M(UP) &= f(UP; M_0, M_{w0}, M_{w1}) \\ \mu_H(UP) &= g(UP; H_0, H_1, H_{w0}, H_{w1}) \\ \mu_{Lo}(SE) &= g(SE; Lo_0, Lo_1, Lo_{w0}, Lo_{w1}) \\ \mu_{Mu}(SE) &= f(SE; Mu_0, Mu_{w0}, Mu_{w1}) \\ \mu_{Hi}(SE) &= g(SE; Hi_0, Hi_1, Hi_{w0}, Hi_{w1}) \end{aligned}$$



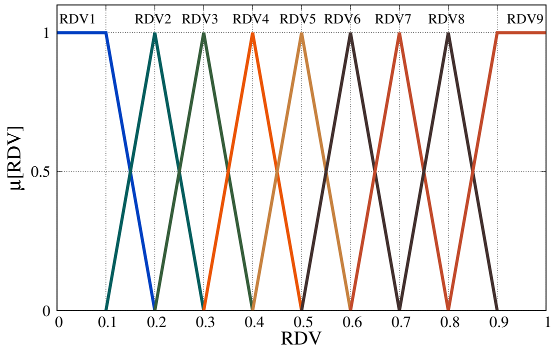
(a) Coverage (b) User Priority



(c) Spectral Efficiency (d) RAT Load



(e) Quality of Experience (f) RDV for FRSM1



(g) RDV for FRSM2 and FRSM3

FIGURE 8.4: Membership functions FRSM1, FRSM2 and FRSM3.

TABLE 8.1: FRB for FRSM1.

Rule	CV	UP	SE	RDV
1	S	L	Lo	RDV1
2	S	L	Mu	RDV2
3	S	L	Hi	RDV3
4	S	M	Lo	RDV2
5	S	M	Mu	RDV3
6	S	M	Hi	RDV4
7	S	H	Lo	RDV3
8	S	H	Mu	RDV4
9	S	H	Hi	RDV5
10	I	L	Lo	RDV2
11	I	L	Mu	RDV3
12	I	L	Hi	RDV4
13	I	M	Lo	RDV3
14	I	M	Mu	RDV4
15	I	M	Hi	RDV5
16	I	H	Lo	RDV4
17	I	H	Mu	RDV5
18	I	H	Ho	RDV6
19	B	L	Lo	RDV3
20	B	L	Mu	RDV4
21	B	L	Hi	RDV5
22	B	M	Lo	RDV4
23	B	M	Mu	RDV5
24	B	M	Hi	RDV6
25	B	H	Lo	RDV5
26	B	H	Mu	RDV6
27	B	H	Hi	RDV7

The term set of output linguistic parameter RDV is defined as follows.

$$RDV = \begin{pmatrix} RadioAccessTechnologyDecisionValue\ L1 \\ RadioAccessTechnologyDecisionValue\ L2 \\ RadioAccessTechnologyDecisionValue\ L3 \\ RadioAccessTechnologyDecisionValue\ L4 \\ RadioAccessTechnologyDecisionValue\ L5 \\ RadioAccessTechnologyDecisionValue\ L6 \\ RadioAccessTechnologyDecisionValue\ L7 \end{pmatrix} = \begin{pmatrix} RDV1 \\ RDV2 \\ RDV3 \\ RDV4 \\ RDV5 \\ RDV6 \\ RDV7 \end{pmatrix}$$

While, the membership functions are defined as follows.

$$\begin{aligned} \mu_{RDV1}(RDV) &= g(RDV; RDV1_0, RDV1_1, RDV1_{w0}, RDV1_{w1}) \\ \mu_{RDV2}(RDV) &= f(RDV; RDV2_0, RDV2_{w0}, RDV2_{w1}) \end{aligned}$$

$$
\begin{aligned}
\mu_{RDV3}(RDV) &= f(RDV; RDV3_0, RDV3_{w0}, RDV3_{w1}) \\
\mu_{RDV4}(RDV) &= f(RDV; RDV4_0, RDV4_{w0}, RDV4_{w1}) \\
\mu_{RDV5}(RDV) &= f(RDV; RDV5_0, RDV5_{w0}, RDV5_{w1}) \\
\mu_{RDV6}(RDV) &= f(RDV; RDV6_0, RDV6_{w0}, RDV6_{w1}) \\
\mu_{RDV7}(RDV) &= g(RDV; RDV7_0, RDV7_1, RDV7_{w0}, RDV7_{w1})
\end{aligned}
$$

8.2.2 Structure of FRSM2 Considering CV, UP, SE and RL

In FRSM2, we considered four parameters: CV, UP, SE and RAT Load (RL), which is a new input parameter for calculating RDV. The structures of FRSM2 is shown in Fig. 8.5.

RAT Load (RL): The load in terms of the number of attached users to each RAT and the number of bearers per UE (refers to how many such virtual network paths or channels are established between the network and a single UE at any given time).

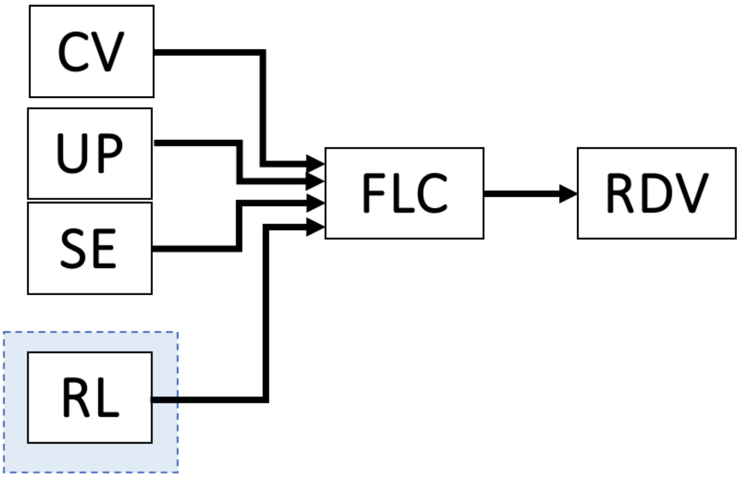


FIGURE 8.5: Proposed system structures for FRSM2.

TABLE 8.2: Parameter and their term sets for FRSM2.

Parameters	Term Sets
Coverage (CV)	Small (Sa), Intermediate (Ie), Big (Bi)
User Priority (UP)	Low (Lo), Medium (Me), High (Hg)
Spectral Efficiency (SE)	Low (Lw), Medium (Mi), High (Hi)
RAT Load (RL)	Very Low Load (VLL), Low Load (LL) Medium Load (ML),High Load (HL), Critical Load (CL)
RAT Decision Value (RDV)	RDV1, RDV2, RDV3, RDV4, RDV5, RDV6, RDV7, RDV8, RDV9

We show parameters and their term sets in Table 8.2. These membership functions for FRMS2 are depicted in Figure 8.4, illustrating how they categorize input variables into fuzzy sets. FRB for FRSM2, detailed in Table 8.3, comprises 135 rules. The formulation of the control rules adheres to the "IF condition THEN control action" structure, allowing for nuanced decision-making that mimics human reasoning. An exemplar of such a rule, Rule 135, demonstrates this logic: "IF CV is Big, UP is High, SE is High and RL is Critical Load, THEN RDV is RDV8".

8.2.3 Structure of FRSM3 Considering CV, UP, SE and QoE

In FRSM3, we considered four parameters: CV, UP, SE and QoE, which is a new input parameter for calculating RDV. The structures of FRSM3 is shown in Fig. 8.6.

Quality of Experience (QoE): The QoE representing the overall user satisfaction, is intricately linked to the RAT in use. The choice and performance of a RAT directly impact the quality and reliability of a service as perceived by the user. While advanced RATs like 5G promise faster data rates and lower latency, the actual QoE is also influenced by factors such as seamless transitions between RATs and coverage consistency. Thus, for optimal user experience, it's crucial to ensure not only the deployment of advanced RATs but also smooth interoperability and comprehensive coverage.

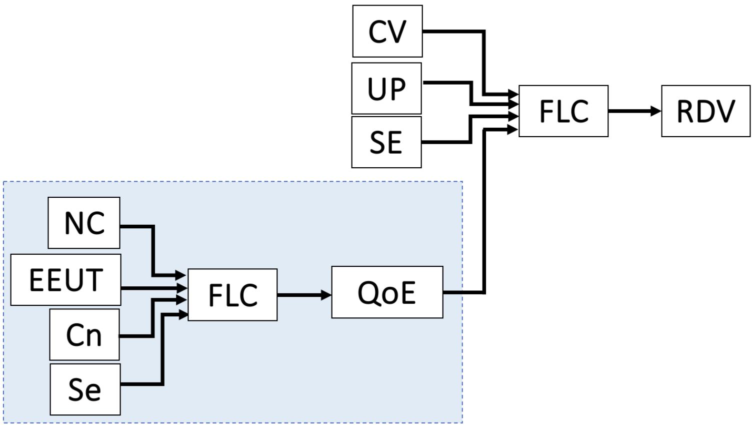


FIGURE 8.6: Proposed system structures for FRSM3.

We explain the design of FLC in following for an new input parameter and its term set are as follows.

$$T(QoE) = \{VeryBad\ (VB), Bad\ (B), Moderate\ (M), Good\ (G), VeryGood\ (VG)\}$$

The membership function for input parameters are defined as follows.

$$\mu_S(CV) = g(CV; S_0, S_1, S_{w0}, S_{w1})$$

TABLE 8.3: FRB for FRSM2.

Rule	CV	UP	SE	RL	RDV	Rule	CV	UP	SE	RL	RDV
1	Sa	Lo	Lw	VLL	RDV2	68	Ie	Me	Mi	ML	RDV5
2	Sa	Lo	Lw	LL	RDV1	69	Ie	Me	Mi	HL	RDV4
3	Sa	Lo	Lw	ML	RDV1	70	Ie	Me	Mi	CL	RDV3
4	Sa	Lo	Lw	HL	RDV1	71	Ie	Me	Hi	VLL	RDV8
5	Sa	Lo	Lw	CL	RDV1	72	Ie	Me	Hi	LL	RDV7
6	Sa	Lo	Mi	VLL	RDV3	73	Ie	Me	Hi	ML	RDV6
7	Sa	Lo	Mi	LL	RDV2	74	Ie	Me	Hi	HL	RDV5
8	Sa	Lo	Mi	ML	RDV1	75	Ie	Me	Hi	CL	RDV4
9	Sa	Lo	Mi	HL	RDV1	76	Ie	Hg	Lw	VLL	RDV7
10	Sa	Lo	Mi	CL	RDV1	77	Ie	Hg	Lw	LL	RDV5
11	Sa	Lo	Hi	VLL	RDV5	78	Ie	Hg	Lw	ML	RDV4
12	Sa	Lo	Hi	LL	RDV3	79	Ie	Hg	Lw	HL	RDV3
13	Sa	Lo	Hi	ML	RDV2	80	Ie	Hg	Lw	CL	RDV2
14	Sa	Lo	Hi	HL	RDV2	81	Ie	Hg	Mi	VLL	RDV8
15	Sa	Lo	Hi	CL	RDV1	82	Ie	Hg	Mi	LL	RDV7
16	Sa	Me	Lw	VLL	RDV3	83	Ie	Hg	Mi	ML	RDV6
17	Sa	Me	Lw	LL	RDV2	84	Ie	Hg	Mi	HL	RDV5
18	Sa	Me	Lw	ML	RDV1	85	Ie	Hg	Mi	CL	RDV4
19	Sa	Me	Lw	HL	RDV1	86	Ie	Hg	Hi	VLL	RDV9
20	Sa	Me	Lw	CL	RDV1	87	Ie	Hg	Hi	LL	RDV8
21	Sa	Me	Mi	VLL	RDV5	88	Ie	Hg	Hi	ML	RDV7
22	Sa	Me	Mi	LL	RDV4	89	Ie	Hg	Hi	HL	RDV6
23	Sa	Me	Mi	ML	RDV3	90	Ie	Hg	Hi	CL	RDV5
24	Sa	Me	Mi	HL	RDV2	91	Bi	Lo	Lw	VLL	RDV6
25	Sa	Me	Mi	CL	RDV1	92	Bi	Lo	Lw	LL	RDV5
26	Sa	Me	Hi	VLL	RDV6	93	Bi	Lo	Lw	ML	RDV4
27	Sa	Me	Hi	LL	RDV5	94	Bi	Lo	Lw	HL	RDV3
28	Sa	Me	Hi	ML	RDV4	95	Bi	Lo	Lw	CL	RDV2
29	Sa	Me	Hi	HL	RDV3	96	Bi	Lo	Mi	VLL	RDV8
30	Sa	Me	Hi	CL	RDV2	97	Bi	Lo	Mi	LL	RDV7
31	Sa	Hg	Lw	VLL	RDV5	98	Bi	Lo	Mi	ML	RDV6
32	Sa	Hg	Lw	LL	RDV3	99	Bi	Lo	Mi	HL	RDV4
33	Sa	Hg	Lw	ML	RDV2	100	Bi	Lo	Mi	CL	RDV3
34	Sa	Hg	Lw	HL	RDV2	101	Bi	Lo	Hi	VLL	RDV9
35	Sa	Hg	Lw	CL	RDV1	102	Bi	Lo	Hi	LL	RDV8
36	Sa	Hg	Mi	VLL	RDV6	103	Bi	Lo	Hi	ML	RDV7
37	Sa	Hg	Mi	LL	RDV5	104	Bi	Lo	Hi	HL	RDV6
38	Sa	Hg	Mi	ML	RDV4	105	Bi	Lo	Hi	CL	RDV5
39	Sa	Hg	Mi	HL	RDV3	106	Bi	Me	Lw	VLL	RDV8
40	Sa	Hg	Mi	CL	RDV2	107	Bi	Me	Lw	LL	RDV7
41	Sa	Hg	Hi	VLL	RDV8	108	Bi	Me	Lw	ML	RDV6
42	Sa	Hg	Hi	LL	RDV6	109	Bi	Me	Lw	HL	RDV5
43	Sa	Hg	Hi	ML	RDV5	110	Bi	Me	Lw	CL	RDV3
44	Sa	Hg	Hi	HL	RDV4	111	Bi	Me	Mi	VLL	RDV9
45	Sa	Hg	Hi	CL	RDV3	112	Bi	Me	Mi	LL	RDV8
46	Ie	Lo	Lw	VLL	RDV3	113	Bi	Me	Mi	ML	RDV7
47	Ie	Lo	Lw	LL	RDV2	114	Bi	Me	Mi	HL	RDV6
48	Ie	Lo	Lw	ML	RDV2	115	Bi	Me	Mi	CL	RDV5
49	Ie	Lo	Lw	HL	RDV1	116	Bi	Me	Hi	VLL	RDV9
50	Ie	Lo	Lw	CL	RDV1	117	Bi	Me	Hi	LL	RDV9
51	Ie	Lo	Mi	VLL	RDV5	118	Bi	Me	Hi	ML	RDV8
52	Ie	Lo	Mi	LL	RDV4	119	Bi	Me	Hi	HL	RDV8
53	Ie	Lo	Mi	ML	RDV3	120	Bi	Me	Hi	CL	RDV7
54	Ie	Lo	Mi	HL	RDV2	121	Bi	Hg	Lw	VLL	RDV9
55	Ie	Lo	Mi	CL	RDV1	122	Bi	Hg	Lw	LL	RDV8
56	Ie	Lo	Hi	VLL	RDV7	123	Bi	Hg	Lw	ML	RDV7
57	Ie	Lo	Hi	LL	RDV5	124	Bi	Hg	Lw	HL	RDV6
58	Ie	Lo	Hi	ML	RDV4	125	Bi	Hg	Lw	CL	RDV5
59	Ie	Lo	Hi	HL	RDV3	126	Bi	Hg	Mi	VLL	RDV9
60	Ie	Lo	Hi	CL	RDV2	127	Bi	Hg	Mi	LL	RDV9
61	Ie	Me	Lw	VLL	RDV5	128	Bi	Hg	Mi	ML	RDV8
62	Ie	Me	Lw	LL	RDV4	129	Bi	Hg	Mi	HL	RDV8
63	Ie	Me	Lw	ML	RDV3	130	Bi	Hg	Mi	CL	RDV7
64	Ie	Me	Lw	HL	RDV2	131	Bi	Hg	Hi	VLL	RDV9
65	Ie	Me	Lw	CL	RDV1	132	Bi	Hg	Hi	LL	RDV9
66	Ie	Me	Mi	VLL	RDV7	133	Bi	Hg	Hi	ML	RDV9
67	Ie	Me	Mi	LL	RDV6	134	Bi	Hg	Hi	HL	RDV9
						135	Bi	Hg	Hi	CL	RDV8

$$\begin{aligned}
\mu_I(CV) &= f(CV; I_0, I_1, I_{w0}, I_{w1}) \\
\mu_B(CV) &= g(CV; B_0, B_1, B_{w0}, B_{w1}) \\
\mu_L(UP) &= g(UP; L_0, L_1, L_{w0}, L_{w1}) \\
\mu_M(UP) &= f(UP; M_0, M_{w0}, M_{w1}) \\
\mu_H(UP) &= g(UP; H_0, H_1, H_{w0}, H_{w1}) \\
\mu_{Lo}(SE) &= g(SE; Lo_0, Lo_1, Lo_{w0}, Lo_{w1}) \\
\mu_{Mu}(SE) &= f(SE; Mu_0, Mu_{w0}, Mu_{w1}) \\
\mu_{Hi}(SE) &= g(SE; Hi_0, Hi_1, Hi_{w0}, Hi_{w1})
\end{aligned}$$

The term set of output linguistic parameter RDV is defined as follows.

$$RDV = \begin{pmatrix} RadioAccessTechnologyDecisionValue\ L1 \\ RadioAccessTechnologyDecisionValue\ L2 \\ RadioAccessTechnologyDecisionValue\ L3 \\ RadioAccessTechnologyDecisionValue\ L4 \\ RadioAccessTechnologyDecisionValue\ L5 \\ RadioAccessTechnologyDecisionValue\ L6 \\ RadioAccessTechnologyDecisionValue\ L7 \\ RadioAccessTechnologyDecisionValue\ L8 \\ RadioAccessTechnologyDecisionValue\ L9 \end{pmatrix} = \begin{pmatrix} RDV1 \\ RDV2 \\ RDV3 \\ RDV4 \\ RDV5 \\ RDV6 \\ RDV7 \\ RDV8 \\ RDV9 \end{pmatrix}$$

While, the membership functions for FRSM3 are defined as follows.

$$\begin{aligned}
\mu_{RDV1}(RDV) &= g(RDV; RDV1_0, RDV1_1, RDV1_{w0}, RDV1_{w1}) \\
\mu_{RDV2}(RDV) &= f(RDV; RDV2_0, RDV2_{w0}, RDV2_{w1}) \\
\mu_{RDV3}(RDV) &= f(RDV; RDV3_0, RDV3_{w0}, RDV3_{w1}) \\
\mu_{RDV4}(RDV) &= f(RDV; RDV4_0, RDV4_{w0}, RDV4_{w1}) \\
\mu_{RDV5}(RDV) &= f(RDV; RDV5_0, RDV5_{w0}, RDV5_{w1}) \\
\mu_{RDV6}(RDV) &= f(RDV; RDV6_0, RDV6_{w0}, RDV6_{w1}) \\
\mu_{RDV7}(RDV) &= f(RDV; RDV7_0, RDV7_{w0}, RDV7_{w1}) \\
\mu_{RDV8}(RDV) &= f(RDV; RDV8_0, RDV8_{w0}, RDV8_{w1}) \\
\mu_{RDV9}(RDV) &= g(RDV; RDV9_0, RDV9_1, RDV9_{w0}, RDV9_{w1})
\end{aligned}$$

We show parameters and their term sets in Table 8.4. The FRB is shown in Table 8.5 and has 135 rules. The control rules have the form: IF "condition" THEN "control action". For example, for Rule 135:"IF CV is Big, UP is High, SE is High and QoE is Very Good, THEN RDV is RDV9".

The QoE is one of the important parameters for the selection of RAT in 5G wireless

TABLE 8.4: Parameter and their term sets for FRSM3.

Parameters	Term Sets
Coverage (CV)	Small (S), Intermediate (I), Big (B)
User Priority (UP)	Low (L),Medium (M) , High (H)
Spectral Efficiency (SE)	Low (Lo), Medium (Mu), High (Hi)
Quality of Experience (QoE)	Very Bad (VB), Bad (B), Moderate (M), Good (G), Very Good (VG)
RAT Decision Value (RDV)	RDV1, RDV2, RDV3, RDV4, RDV5, RDV6, RDV7, RDV8, RDV9

networks. The QoE isn't just a standalone metric but is intricately interwoven with multiple network parameters. A well-balanced combination of high network capacity, optimum end-user throughput, and consistent connectivity ensures that users enjoy a superior and satisfactory digital experience. The continual monitoring and optimization of these parameters are essential for service providers to deliver and maintain high QoE levels. For this reason, in this paper, we propose a Fuzzy-based Scheme for QoE Evaluation (FSQoE). The FSQoE1 considering three parameters: Network Capacity (NC), Experienced End-User Throughput (EEUT) and Connectivity (Cn).

Fuzzy-based Scheme for QoE Evaluation: FSQoE1

In Fig. 8.7, we use three input parameters and one output parameter for FSQoE1 as follow:

Network Capacity (NC): As the term suggests, network capacity denotes the maximum traffic volume a network can handle efficiently at any given point. It's a crucial parameter as a network with higher capacity can accommodate more users and data, leading to reduced congestion and lag. When the NC value is high, it indicates that the network is capable of supporting higher data volumes, resulting in smoother service delivery and subsequently, a heightened QoE.

Experienced End-User Throughput (EEUT): Throughput is essentially the actual data transfer rate a user experiences. It's a direct indicator of how swiftly data can be sent or received over the network. A higher EEUT means faster download and upload speeds, quicker video buffering, and more responsive online gaming or browsing. Therefore, when users experience a high throughput, they can access and interact with online services more seamlessly, elevating their overall satisfaction.

Connectivity (Cn): This pertains to the strength and stability of a user's connection to a Radio Access Technology (RAT). In the world of mobile communications, being able to maintain a stable and strong connection is paramount. When users consistently have good connectivity, they face fewer disruptions, like call drops or interrupted streaming, which translates to a higher QoE.

TABLE 8.5: FRB for FRSM3.

Rule	CV	UP	SE	QoE	RDV	Rule	CV	UP	SE	QoE	RDV
1	S	L	Lo	VB	RDV1	68	I	M	Mu	Mo	RDV5
2	S	L	Lo	B	RDV1	69	I	M	Mu	G	RDV6
3	S	L	Lo	Mo	RDV1	70	I	M	Mu	VG	RDV7
4	S	L	Lo	G	RDV1	71	I	M	Hi	VB	RDV4
5	S	L	Lo	VG	RDV2	72	I	M	Hi	B	RDV5
6	S	L	Mu	VB	RDV1	73	I	M	Hi	Mo	RDV6
7	S	L	Mu	B	RDV1	74	I	M	Hi	G	RDV7
8	S	L	Mu	Mo	RDV1	75	I	M	Hi	VG	RDV8
9	S	L	Mu	G	RDV2	76	I	H	Lo	VB	RDV3
10	S	L	Mu	VG	RDV3	77	I	H	Lo	B	RDV4
11	S	L	Hi	VB	RDV1	78	I	H	Lo	Mo	RDV5
12	S	L	Hi	B	RDV2	79	I	H	Lo	G	RDV6
13	S	L	Hi	Mo	RDV2	80	I	H	Lo	VG	RDV7
14	S	L	Hi	G	RDV3	81	I	H	Mu	VB	RDV4
15	S	L	Hi	VG	RDV5	82	I	H	Mu	B	RDV5
16	S	M	Lo	VB	RDV1	83	I	H	Mu	Mo	RDV6
17	S	M	Lo	B	RDV1	84	I	H	Mu	G	RDV8
18	S	M	Lo	Mo	RDV1	85	I	H	Mu	VG	RDV8
19	S	M	Lo	G	RDV2	86	I	H	Hi	VB	RDV6
20	S	M	Lo	VG	RDV3	87	I	H	Hi	B	RDV7
21	S	M	Mu	VB	RDV1	88	I	H	Hi	Mo	RDV8
22	S	M	Mu	B	RDV2	89	I	H	Hi	G	RDV9
23	S	M	Mu	Mo	RDV2	90	I	H	Hi	VG	RDV9
24	S	M	Mu	G	RDV3	91	B	L	Lo	VB	RDV2
25	S	M	Mu	VG	RDV5	92	B	L	Lo	B	RDV3
26	S	M	Hi	VB	RDV2	93	B	L	Lo	Mo	RDV4
27	S	M	Hi	B	RDV3	94	B	L	Lo	G	RDV5
28	S	M	Hi	Mo	RDV4	95	B	L	Lo	VG	RDV6
29	S	M	Hi	G	RDV5	96	B	L	Mu	VB	RDV4
30	S	M	Hi	VG	RDV6	97	B	L	Mu	B	RDV5
31	S	H	Lo	VB	RDV1	98	B	L	Mu	Mo	RDV6
32	S	H	Lo	B	RDV2	99	B	L	Mu	G	RDV7
33	S	H	Lo	Mo	RDV2	100	B	L	Mu	VG	RDV8
34	S	H	Lo	G	RDV3	101	B	L	Hi	VB	RDV5
35	S	H	Lo	VG	RDV5	102	B	L	Hi	B	RDV6
36	S	H	Mu	VB	RDV2	103	B	L	Hi	Mo	RDV7
37	S	H	Mu	B	RDV3	104	B	L	Hi	G	RDV8
38	S	H	Mu	Mo	RDV4	105	B	L	Hi	VG	RDV9
39	S	H	Mu	G	RDV5	106	B	M	Lo	VB	RDV3
40	S	H	Mu	VG	RDV6	107	B	M	Lo	B	RDV5
41	S	H	Hi	VB	RDV4	108	B	M	Lo	Mo	RDV6
42	S	H	Hi	B	RDV5	109	B	M	Lo	G	RDV7
43	S	H	Hi	Mo	RDV6	110	B	M	Lo	VG	RDV8
44	S	H	Hi	G	RDV7	111	B	M	Mu	VB	RDV5
45	S	H	Hi	VG	RDV8	112	B	M	Mu	B	RDV6
46	I	L	Lo	VB	RDV1	113	B	M	Mu	Mo	RDV7
47	I	L	Lo	B	RDV1	114	B	M	Mu	G	RDV8
48	I	L	Lo	Mo	RDV2	115	B	M	Mu	VG	RDV9
49	I	L	Lo	G	RDV2	116	B	M	Hi	VB	RDV7
50	I	L	Lo	VG	RDV4	117	B	M	Hi	B	RDV8
51	I	L	Mu	VB	RDV2	118	B	M	Hi	Mo	RDV9
52	I	L	Mu	B	RDV2	119	B	M	Hi	G	RDV9
53	I	L	Mu	Mo	RDV3	120	B	M	Hi	VG	RDV9
54	I	L	Mu	G	RDV4	121	B	H	Lo	VB	RDV5
55	I	L	Mu	VG	RDV6	122	B	H	Lo	B	RDV6
56	I	L	Hi	VB	RDV3	123	B	H	Lo	Mo	RDV7
57	I	L	Hi	B	RDV4	124	B	H	Lo	G	RDV8
58	I	L	Hi	Mo	RDV5	125	B	H	Lo	VG	RDV9
59	I	L	Hi	G	RDV6	126	B	H	Mu	VB	RDV7
60	I	L	Hi	VG	RDV7	127	B	H	Mu	B	RDV8
61	I	M	Lo	VB	RDV2	128	B	H	Mu	Mo	RDV9
62	I	M	Lo	B	RDV2	129	B	H	Mu	G	RDV9
63	I	M	Lo	Mo	RDV3	130	B	H	Mu	VG	RDV9
64	I	M	Lo	G	RDV4	131	B	H	Hi	VB	RDV8
65	I	M	Lo	VG	RDV6	132	B	H	Hi	B	RDV9
66	I	M	Mu	VB	RDV3	133	B	H	Hi	Mo	RDV9
67	I	M	Mu	B	RDV4	134	B	H	Hi	G	RDV9
						135	B	H	Hi	VG	RDV9

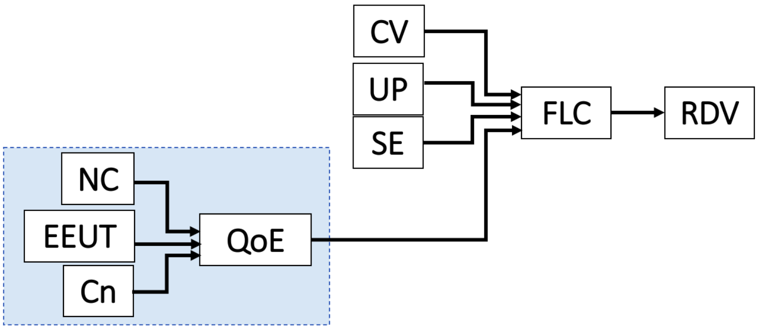


FIGURE 8.7: Proposed system structures for FSQoE1.

TABLE 8.6: Parameter and their term sets for FSQoE1.

Parameters	Term Sets
Network Capacity (CV)	Small (Sm), Intermediate (In), Big (Bi)
Experienced End-User Throughput (EEUT)	Slow (Sl), Medium (Mi) , Fast (Fs)
Connectivity (Cn)	Low (Lo), Medium (Mu), High (Hg)
Quality of Experience (QoE)	QoE1, QoE2, QoE3, QoE4, QoE5, QoE6, QoE7

Quality of Experience (QoE): QoE represents a comprehensive measure of a user's satisfaction with a service, going beyond mere technical metrics to encapsulate the overall user perception and experience.

The membership functions for FSQoE1 are shown in Table 8.6. The FRB for FSQoE1 is shown in Table 8.7 and has 27 rules. The control rules have the form: IF "condition" THEN "control action". For example, for Rule 1:"IF NC is Sm, EEUT is Sl and Cn is Lo, THEN QoE is QoE1".

Fuzzy-based Scheme for QoE Evaluation: FSQoE2

In FSQoE2, we consider 4 parameters: NC, EEUT, Cn and Security (Se) as new parameter. The output parameter is QoE.

Security (Se): Security is paramount in the realm of telecommunications and digital services. As users engage with various online platforms, they often share sensitive and personal information, ranging from contact details to financial data. The assurance that this data is protected and not susceptible to breaches or unauthorized access is a foundational aspect of a user's trust in a network or service.

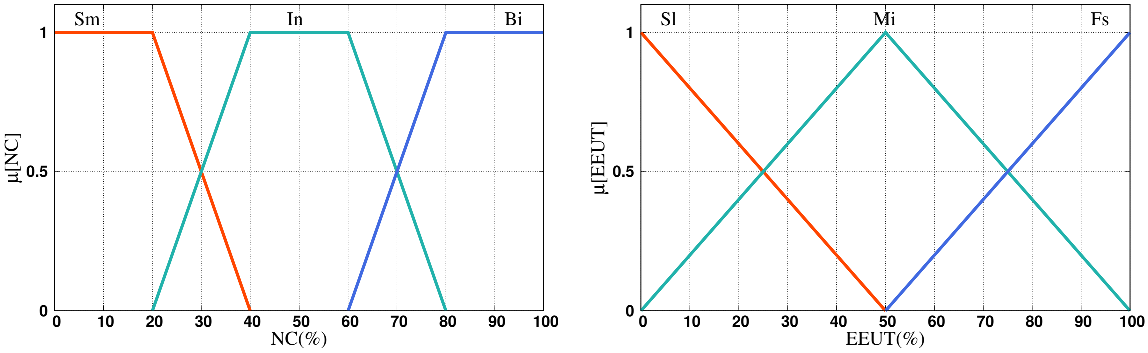
The membership functions are shown in Fig. 8.8. We show parameters and their term sets for FSQoE2 in Table 8.8. The FRB for FSQoE2 is shown in Table 8.9 and has 135 rules. The control rules have the form: IF "condition" THEN "control action". For example, for Rule 1:"IF Network Capacity is Small, Experienced End-User Throughput is Slow, Connectivity is Low and Security is Very Poor, THEN Quality of Experience is Quality of Experience level 1".

TABLE 8.7: FRB for FSQoE1.

Rule	NC	EEUT	Cn	QoE
1	Sm	Sl	Lo	QoE1
2	Sm	Sl	Mu	QoE2
3	Sm	Sl	Hg	QoE3
4	Sm	Mi	Lo	QoE2
5	Sm	Mi	Mu	QoE3
6	Sm	Mi	Hg	QoE4
7	Sm	Fs	Lo	QoE3
8	Sm	Fs	Mu	QoE4
9	Sm	Fs	Hg	QoE5
10	In	Sl	Lo	QoE2
11	In	Sl	Mu	QoE3
12	In	Sl	Hi	QoE4
13	In	Mi	Lo	QoE3
14	In	Mi	Mu	QoE4
15	In	Mi	Hg	QoE5
16	In	Fs	Lo	QoE4
17	In	Fs	Mu	QoE5
18	In	Fs	Hg	QoE6
19	Bi	Sl	Lo	QoE3
20	Bi	Sl	Mu	QoE4
21	Bi	Sl	Hg	QoE5
22	Bi	Mi	Lo	QoE4
23	Bi	Mi	Mu	QoE5
24	Bi	Mi	Hg	QoE6
25	Bi	Fs	Lo	QoE5
26	Bi	Fs	Mu	QoE6
27	Bi	Fs	Hg	QoE7

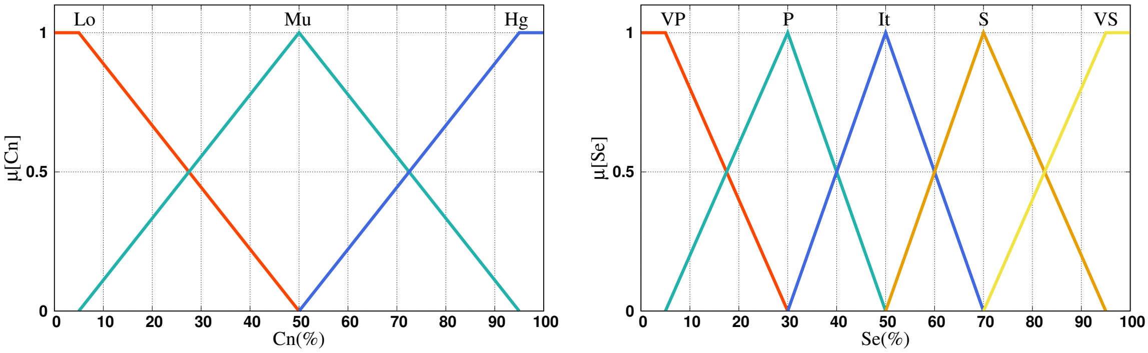
TABLE 8.8: Parameter and their term sets for FSQoE2.

Parameters	Term Sets
Network Capacity (NC)	Small (Sm), Intermediate (In), Big (Bi)
Experienced End-User Throughput (EEUT)	Slow (Sl), Medium (Mi) , Fast (Fs)
Connectivity (Cn)	Low (Lo), Medium (Mu), High (Hg)
Security (Se)	Very Poor (VP), Poor, Intermediate (It), Strong (S), Very Strong (VS)
Quality of Experience (QoE)	QoE1, QoE2, QoE3, QoE4, QoE5, QoE6, QoE7, QoE8, QoE9



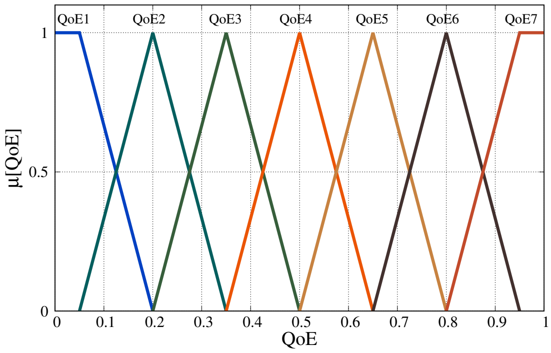
(a) Network Capacity

(b) Experienced End-User Throughput



(c) Connectivity

(d) Security



(e) Quality of Experience

FIGURE 8.8: Membership functions for FSQoE1 and FSQoE2.

TABLE 8.9: FRB for FSQoE2.

Rule	NC	EEUT	Cn	Se	QoE	Rule	NC	EEUT	Cn	Se	QoE
1	Sm	Sl	Lo	VP	QoE1	68	In	Mi	Mu	It	QoE5
2	Sm	Sl	Lo	P	QoE1	69	In	Mi	Mu	S	QoE6
3	Sm	Sl	Lo	It	QoE1	70	In	Mi	Mu	VS	QoE7
4	Sm	Sl	Lo	S	QoE1	71	In	Mi	Hg	VP	QoE4
5	Sm	Sl	Lo	VS	QoE2	72	In	Mi	Hg	P	QoE5
6	Sm	Sl	Mu	VP	QoE1	73	In	Mi	Hg	It	QoE6
7	Sm	Sl	Mu	P	QoE1	74	In	Mi	Hg	S	QoE7
8	Sm	Sl	Mu	It	QoE2	75	In	Mi	Hg	VS	QoE8
9	Sm	Sl	Mu	S	QoE2	76	In	Fs	Lo	VP	QoE3
10	Sm	Sl	Mu	VS	QoE3	77	In	Fs	Lo	P	QoE4
11	Sm	Sl	Hg	VP	QoE1	78	In	Fs	Lo	It	QoE5
12	Sm	Sl	Hg	P	QoE2	79	In	Fs	Lo	S	QoE6
13	Sm	Sl	Hg	It	QoE3	80	In	Fs	Lo	VS	QoE7
14	Sm	Sl	Hg	S	QoE4	81	In	Fs	Mu	VP	QoE4
15	Sm	Sl	Hg	VS	QoE5	82	In	Fs	Mu	P	QoE6
16	Sm	Mi	Lo	VP	QoE1	83	In	Fs	Mu	It	QoE7
17	Sm	Mi	Lo	P	QoE1	84	In	Fs	Mu	S	QoE8
18	Sm	Mi	Lo	It	QoE1	85	In	Fs	Mu	VS	QoE8
19	Sm	Mi	Lo	S	QoE2	86	In	Fs	Hg	VP	QoE6
20	Sm	Mi	Lo	VS	QoE3	87	In	Fs	Hg	P	QoE7
21	Sm	Mi	Mu	VP	QoE1	88	In	Fs	Hg	It	QoE8
22	Sm	Mi	Mu	P	QoE2	89	In	Fs	Hg	S	QoE9
23	Sm	Mi	Mu	It	QoE3	90	In	Fs	Hg	VS	QoE9
24	Sm	Mi	Mu	S	QoE4	91	Bi	Sl	Lo	VP	QoE2
25	Sm	Mi	Mu	VS	QoE5	92	Bi	Sl	Lo	P	QoE3
26	Sm	Mi	Hg	VP	QoE2	93	Bi	Sl	Lo	It	QoE4
27	Sm	Mi	Hg	P	QoE3	94	Bi	Sl	Lo	S	QoE5
28	Sm	Mi	Hg	It	QoE4	95	Bi	Sl	Lo	VS	QoE7
29	Sm	Mi	Hg	S	QoE5	96	Bi	Sl	Mu	VP	QoE4
30	Sm	Mi	Hg	VS	QoE7	97	Bi	Sl	Mu	P	QoE5
31	Sm	Fs	Lo	VP	QoE1	98	Bi	Sl	Mu	It	QoE6
32	Sm	Fs	Lo	P	QoE2	99	Bi	Sl	Mu	S	QoE7
33	Sm	Fs	Lo	It	QoE3	100	Bi	Sl	Mu	VS	QoE8
34	Sm	Fs	Lo	S	QoE4	101	Bi	Sl	Hg	VP	QoE5
35	Sm	Fs	Lo	VS	QoE5	102	Bi	Sl	Hg	P	QoE6
36	Sm	Fs	Mu	VP	QoE2	103	Bi	Sl	Hg	It	QoE7
37	Sm	Fs	Mu	P	QoE3	104	Bi	Sl	Hg	S	QoE8
38	Sm	Fs	Mu	It	QoE4	105	Bi	Sl	Hg	VS	QoE9
39	Sm	Fs	Mu	S	QoE5	106	Bi	Mi	Lo	VP	QoE4
40	Sm	Fs	Mu	VS	QoE7	107	Bi	Mi	Lo	P	QoE5
41	Sm	Fs	Hg	VP	QoE4	108	Bi	Mi	Lo	It	QoE6
42	Sm	Fs	Hg	P	QoE5	109	Bi	Mi	Lo	S	QoE7
43	Sm	Fs	Hg	It	QoE6	110	Bi	Mi	Lo	VS	QoE8
44	Sm	Fs	Hg	S	QoE7	111	Bi	Mi	Mu	VP	QoE5
45	Sm	Fs	Hg	VS	QoE8	112	Bi	Mi	Mu	P	QoE6
46	In	Sl	Lo	VP	QoE1	113	Bi	Mi	Mu	It	QoE7
47	In	Sl	Lo	P	QoE1	114	Bi	Mi	Mu	S	QoE8
48	In	Sl	Lo	It	QoE2	115	Bi	Mi	Mu	VS	QoE9
49	In	Sl	Lo	S	QoE3	116	Bi	Mi	Hg	VP	QoE7
50	In	Sl	Lo	VS	QoE4	117	Bi	Mi	Hg	P	QoE8
51	In	Sl	Mu	VP	QoE2	118	Bi	Mi	Hg	It	QoE8
52	In	Sl	Mu	P	QoE2	119	Bi	Mi	Hg	S	QoE9
53	In	Sl	Mu	It	QoE3	120	Bi	Mi	Hg	VS	QoE9
54	In	Sl	Mu	S	QoE4	121	Bi	Fs	Lo	VP	QoE5
55	In	Sl	Mu	VS	QoE6	122	Bi	Fs	Lo	P	QoE6
56	In	Sl	Hg	VP	QoE3	123	Bi	Fs	Lo	It	QoE7
57	In	Sl	Hg	P	QoE4	124	Bi	Fs	Lo	S	QoE8
58	In	Sl	Hg	It	QoE5	125	Bi	Fs	Lo	VS	QoE9
59	In	Sl	Hg	S	QoE6	126	Bi	Fs	Mu	VP	QoE7
60	In	Sl	Hg	VS	QoE7	127	Bi	Fs	Mu	P	QoE8
61	In	Mi	Lo	VP	QoE2	128	Bi	Fs	Mu	It	QoE9
62	In	Mi	Lo	P	QoE2	129	Bi	Fs	Mu	S	QoE9
63	In	Mi	Lo	It	QoE3	130	Bi	Fs	Mu	VS	QoE9
64	In	Mi	Lo	S	QoE4	131	Bi	Fs	Hg	VP	QoE8
65	In	Mi	Lo	VS	QoE6	132	Bi	Fs	Hg	P	QoE9
66	In	Mi	Mu	VP	QoE3	133	Bi	Fs	Hg	It	QoE9
67	In	Mi	Mu	P	QoE4	134	Bi	Fs	Hg	S	QoE9
						135	Bi	Fs	Hg	VS	QoE9

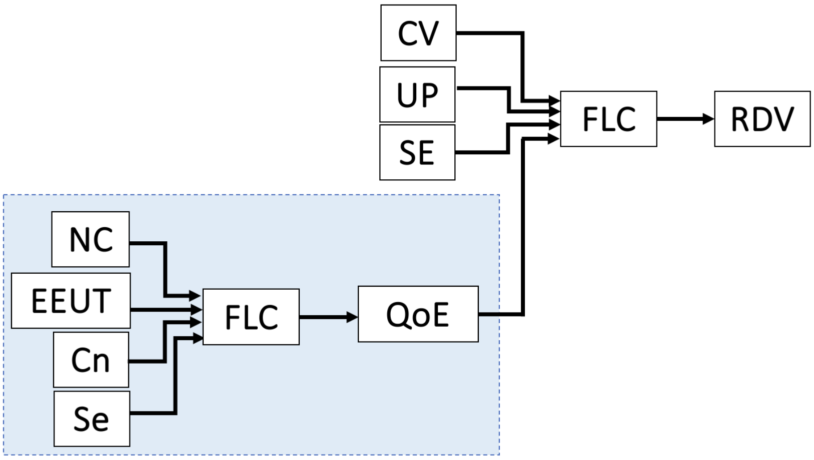


FIGURE 8.9: Proposed system structures for FSQoE2.

8.3 Fuzzy-based Admission Control Module (FACM)

In this PhD thesis, we present a FACM with four input parameters as shown in Fig. 8.10. A detailed description and extensive simulation results of FACM can be found in Master thesis [101].

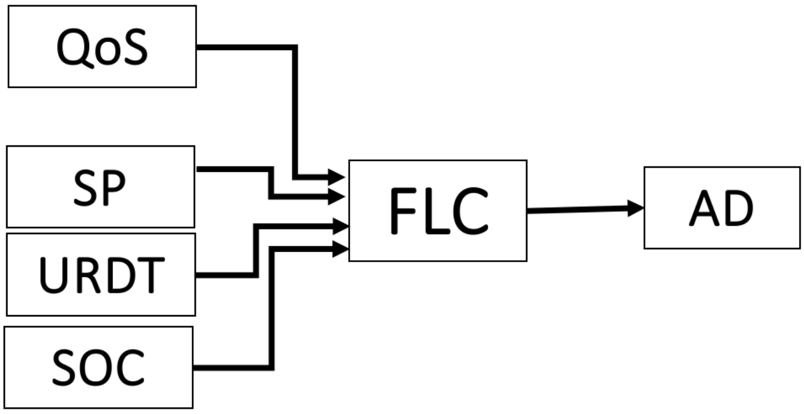


FIGURE 8.10: Proposed system structures for FACM.

Quality of Service (QoS): A user with a high QoS value signifies the importance or priority of the user's data. If a high QoS user requests a connection, the system might give preference to this request over others.

Slice Priority (SP): In environments like 5G, where network slicing is prominent, different slices might cater to different types of services (e.g., IoT, video streaming, virtual reality). High-priority slices might get precedence in the admission process, ensuring critical services remain uninterrupted.

User Request Delay Time (URDT): A prolonged waiting time for a user might negatively affect their experience. Hence, if a user's request has been in the buffer for an extended period, the system might prioritize it to ensure the Quality of Experience (QoE) doesn't degrade.

Slice Overloading Cost (SOC): Before admitting a new connection, the system must also consider the potential overload it might bring to a network slice. If a slice is near its capacity, adding more users might be costly in terms of performance degradation. Hence, slices with a low overloading cost might be more suitable for admitting new connections.

Admission Decision (AD): The Admission Decision is a critical process in network management, especially in systems that handle multiple users and various traffic types. It's the process by which the system determines whether a new connection request from a user or device can be accommodated without compromising the quality of service (QoS) for existing connections.

8.3.1 Design of FLC for FACM

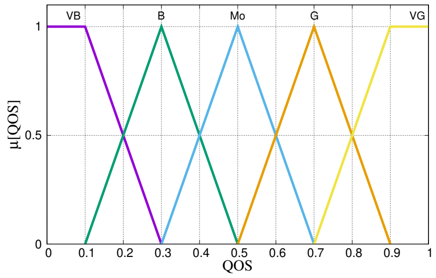
The term sets for each input linguistic parameter are defined respectively as shown in Table 8.10. The FRB for evaluating FACM is shown in Table 8.11 and has 135 rules. The FRB is formed by a fuzzy set of dimensions ($|T(AD|) = |T(QoS)| \times |T(SP)| \times |T(URDT)| \times |T(SOC)|$), where ∣T(x)∣ is the number of terms on T(x). The control rules have the form: IF "condition" THEN "control action". For example, for Rule 1 of FACM: "IF QoS is VB, SP is L, URDT is Sh and SOC is Sm, THEN AD is AD1".

TABLE 8.10: Parameter and their term sets for FACM.

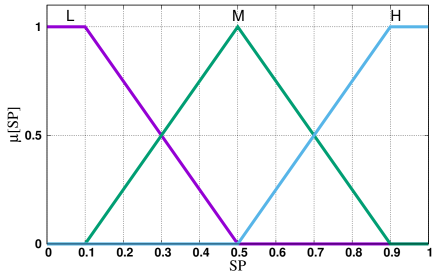
Parameters	Term set
Quality of Service (QoS)	Very Bad (VB), Bad (B),
	Moderate (Mo), Good (G), Very Good (VG)
Slice Priority (SP)	Low (L), Medium (M), High (H)
User Request Delay Time (URDT)	Short (Sh), Medium (Me), Long (Lo)
Slice Overloading Cost (SOC)	Small (Sm), Intermediate (In), Big (Bg)
Admission Decision (AD)	AD1, AD2, AD3, AD4,
	AD5, AD6, AD7, AD8, AD9

$$\begin{aligned}
T(QoS) &= \{VeryBad(VB), Bad(Ba), Moderate(Mo), Good(Gd), VeryGood(VG)\} \\
T(SP) &= \{Low(L), Medium(M), High(H)\} \\
T(URDT) &= \{Short(Sh), Medium(Me), Long(Lo)\} \\
T(SOC) &= \{Small(Sm), Intermediate(In), Huge(Hu)\}
\end{aligned}$$

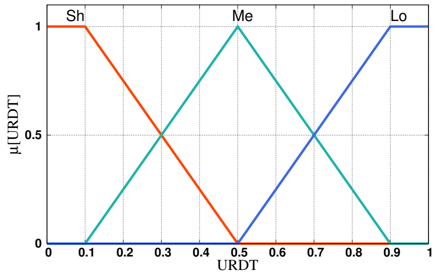
The membership function for input parameters are defined as follows.



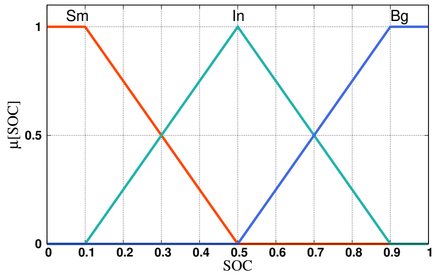
(a) Quality of Service



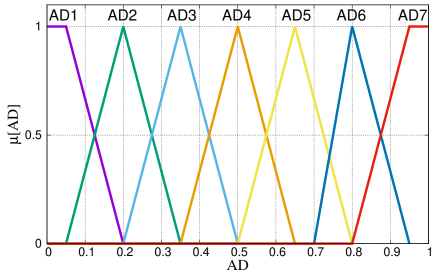
(b) Slice Priority



(c) User Request Delay Time



(d) Slice Overloading Cost



(e) Admission Decision

FIGURE 8.11: Membership functions FACM.

TABLE 8.11: Rule base for FACM.

Rule	QoS	SP	URDT	SOC	AD	Rule	QoS	SP	URDT	SOC	AD	Rule	QoS	SP	URDT	SOC	AD
1	VB	L	Sh	Sm	AD1	46	B	M	Sh	Sm	AD6	91	G	M	Sh	Sm	AD6
2	VB	L	Sh	In	AD1	47	B	H	Sh	In	AD4	92	G	M	Sh	In	AD3
3	VB	L	Sh	Bg	AD1	48	B	H	Sh	Bg	AD2	93	G	M	Sh	Bg	AD2
4	VB	L	Me	Sm	AD2	49	B	H	Me	Sm	AD8	94	G	M	Me	Sm	AD8
5	VB	L	Me	In	AD1	50	B	H	Me	In	AD6	95	G	M	Me	In	AD6
6	VB	L	Me	Bg	AD1	51	B	H	Me	Bg	AD4	96	G	M	Me	Bg	AD4
7	VB	L	Lo	Sm	AD4	52	B	H	Lo	Sm	AD9	97	G	M	Lo	Sm	AD9
8	VB	L	Lo	In	AD2	53	B	H	Lo	In	AD8	98	G	M	Lo	In	AD8
9	VB	L	Lo	Bg	AD1	54	B	H	Lo	Bg	AD7	99	G	M	Lo	Bg	AD6
10	VB	M	Sh	Sm	AD2	55	Mo	L	Sh	Sm	AD2	100	G	H	Sh	Sm	AD8
11	VB	M	Sh	In	AD1	56	Mo	L	Sh	In	AD1	101	G	H	Sh	In	AD6
12	VB	M	Sh	Bg	AD1	57	Mo	L	Sh	Bg	AD1	102	G	H	Sh	Bg	AD4
13	VB	M	Me	Sm	AD4	58	Mo	L	Me	Sm	AD4	103	G	H	Me	Sm	AD9
14	VB	M	Me	In	AD2	59	Mo	L	Me	In	AD2	104	G	H	Me	In	AD8
15	VB	M	Me	Bg	AD1	60	Mo	L	Me	Bg	AD1	105	G	H	Me	Bg	AD6
16	VB	M	Lo	Sm	AD7	61	Mo	L	Lo	Sm	AD7	106	G	H	Lo	Sm	AD9
17	VB	M	Lo	In	AD4	62	Mo	L	Lo	In	AD4	107	G	H	Lo	In	AD9
18	VB	M	Lo	Bg	AD2	63	Mo	L	Lo	Bg	AD3	108	G	H	Lo	Bg	AD8
19	VB	H	Sh	Sm	AD5	64	Mo	M	Sh	Sm	AD5	109	VG	L	Sh	Sm	AD5
20	VB	H	Sh	In	AD2	65	Mo	M	Sh	In	AD2	110	VG	L	Sh	In	AD3
21	VB	H	Sh	Bg	AD1	66	Mo	M	Sh	Bg	AD1	111	VG	L	Sh	Bg	AD2
22	VB	H	Me	Sm	AD7	67	Mo	M	Me	Sm	AD7	112	VG	L	Me	Sm	AD8
23	VB	H	Me	In	AD5	68	Mo	M	Me	In	AD5	113	VG	L	Me	In	AD5
24	VB	H	Me	Bg	AD3	69	Mo	M	Me	Bg	AD3	114	VG	L	Me	Bg	AD3
25	VB	H	Lo	Sm	AD9	70	Mo	M	Lo	Sm	AD9	115	VG	L	Lo	Sm	AD9
26	VB	H	Lo	In	AD7	71	Mo	M	Lo	In	AD7	116	VG	L	Lo	In	AD8
27	VB	H	Lo	Bg	AD5	72	Mo	M	Lo	Bg	AD5	117	VG	L	Lo	Bg	AD6
28	B	L	Sh	Sm	AD2	73	Mo	H	Sh	Sm	AD7	118	VG	M	Sh	Sm	AD8
29	B	L	Sh	In	AD1	74	Mo	H	Sh	In	AD5	119	VG	M	Sh	In	AD5
30	B	L	Sh	Bg	AD1	75	Mo	H	Sh	Bg	AD3	120	VG	M	Sh	Bg	AD4
31	B	L	Me	Sm	AD4	76	Mo	H	Me	Sm	AD9	121	VG	M	Me	Sm	AD9
32	B	L	Me	In	AD2	77	Mo	H	Me	In	AD7	122	VG	M	Me	In	AD8
33	B	L	Me	Bg	AD1	78	Mo	H	Me	Bg	AD5	123	VG	M	Me	Bg	AD6
34	B	L	Lo	Sm	AD6	79	Mo	H	Lo	Sm	AD9	124	VG	M	Lo	Sm	AD9
35	B	L	Lo	In	AD4	80	Mo	H	Lo	In	AD9	125	VG	M	Lo	In	AD9
36	B	L	Lo	Bg	AD2	81	Mo	H	Lo	Bg	AD8	126	VG	M	Lo	Bg	AD8
37	B	M	Sh	Sm	AD4	82	G	L	Sh	Sm	AD3	127	VG	H	Sh	Sm	AD9
38	B	M	Sh	In	AD2	83	G	L	Sh	In	AD1	128	VG	H	Sh	In	AD8
39	B	M	Sh	Bg	AD1	84	G	L	Sh	Bg	AD1	129	VG	H	Sh	Bg	AD6
40	B	M	Me	Sm	AD6	85	G	L	Me	Sm	AD5	130	VG	H	Me	Sm	AD9
41	B	M	Me	In	AD4	86	G	L	Me	In	AD3	131	VG	H	Me	In	AD9
42	B	M	Me	Bg	AD2	87	G	L	Me	Bg	AD2	132	VG	H	Me	Bg	AD8
43	B	M	Lo	Sm	AD8	88	G	L	Lo	Sm	AD8	133	VG	H	Lo	Sm	AD9
44	B	M	Lo	In	AD6	89	G	L	Lo	In	AD5	134	VG	H	Lo	In	AD9
45	B	M	Lo	Bg	AD4	90	G	L	Lo	Bg	AD4	135	VG	H	Lo	Bg	AD9

$$\begin{aligned}
\mu_{VB}(QoS) &= g(QoS; VB_0, VB_1, VB_{w0}, VB_{w1}) \\
\mu_{B}(QoS) &= f(QoS; B_0, B_{w0}, B_{w1}) \\
\mu_{In}(QoS) &= f(QoS; In_0, In_{w0}, In_{w1}) \\
\mu_{G}(QoS) &= f(QoS; G_0, G_{w0}, G_{w1}) \\
\mu_{VG}(QoS) &= g(GS; VG_0, VG_1, VG_{w0}, VG_{w1}) \\
\mu_{L}(SP) &= g(SP; L_0, L_1, L_{w0}, L_{w1}) \\
\mu_{M}(SP) &= f(SP; M_0, M_{w0}, M_{w1}) \\
\mu_{H}(SP) &= g(SP; H_0, H_1, H_{w0}, H_{w1}) \\
\mu_{Sh}(URDT) &= g(URDT; Sh_0, Sh_1, Sh_{w0}, Sh_{w1}) \\
\mu_{Me}(URDT) &= f(URDT; Me_0, Me_{w0}, Me_{w1})
\end{aligned}$$

$$\begin{aligned}
\mu_{Lo}(URDT) &= g(UDRT; Lo_0, Lo_1, Lo_{w0}, Lo_{w1}) \\
\mu_{Sm}(SOC) &= g(NSS; Sm_0, Sm_1, Sm_{w0}, Sm_{w1}) \\
\mu_{In}(SOC) &= f(NSS; In_0, In_{w0}, In_{w1}) \\
\mu_{Bg}(SOC) &= g(NSS; Bg_0, Bg_1, Bg_{w0}, Bg_{w1})
\end{aligned}$$

The output linguistic parameter is Admission Decision (AD).The term set for the output parameter AD is defined as follows.

$$AD = \begin{pmatrix} Admission\ Decision\ L1 \\ Admission\ Decision\ L2 \\ Admission\ Decision\ L3 \\ Admission\ Decision\ L4 \\ Admission\ Decision\ L5 \\ Admission\ Decision\ L6 \\ Admission\ Decision\ L7 \end{pmatrix} = \begin{pmatrix} AD1 \\ AD2 \\ AD3 \\ AD4 \\ AD5 \\ AD6 \\ AD7 \end{pmatrix}$$

The membership functions for the output parameter AD are defined as follows.

$$\begin{aligned}
\mu_{AD1}(AD) &= g(AD; AD1_0, AD1_1, AD1_{w0}, AD1_{w1}) \\
\mu_{AD2}(AD) &= f(AD; AD2_0, AD2_{w0}, AD2_{w1}) \\
\mu_{AD3}(AD) &= f(AD; AD3_0, AD3_{w0}, AD3_{w1}) \\
\mu_{AD4}(AD) &= f(AD; AD4_0, AD4_{w0}, AD4_{w1}) \\
\mu_{AD5}(AD) &= f(AD; AD5_0, AD5_{w0}, AD5_{w1}) \\
\mu_{AD6}(AD) &= f(AD; AD6_0, AD6_{w0}, AD6_{w1}) \\
\mu_{AD7}(AD) &= g(AD; AD7_0, AD7_1, AD7_{w0}, AD7_{w1})
\end{aligned}$$

8.4 Fuzzy-based Handover Module (FHM)

The proposed system is called Fuzzy-Based Handover System (FBHS) in 5G Wireless Networks. The structure of FBMS is shown in Fig. 8.12. We implement two models: FBHM1 and FBHM2. The FBHM1 considers three input parameters: Slice Delay (SD), Slice Bandwidth (SB), Slice Stability (SS) and the output parameter is Handover Decision (HD). In FBHM2, we consider Slice Load (SL) as a new parameter.

The considered parameters are explained in following.

Slice Delay (SD): Delay within a network slice can be attributed to factors like queueing of data packets and inherent network latencies. High slice delays can degrade the QoS, making real-time services like voice calls or video streaming less

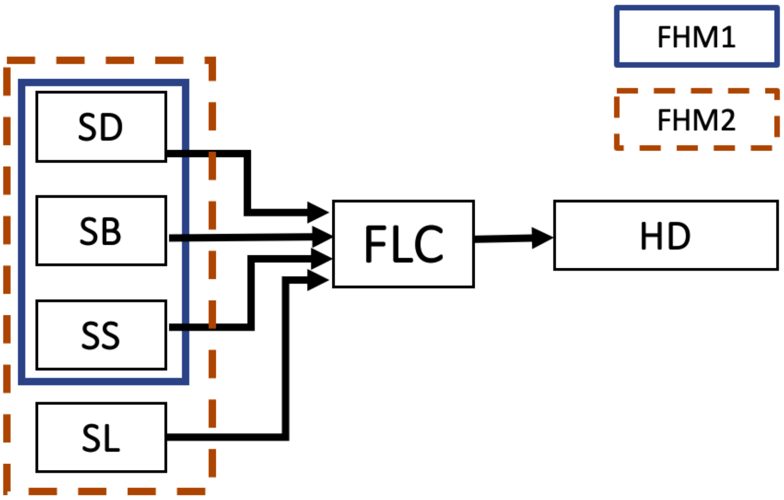


FIGURE 8.12: Proposed system structures for FHM1 and FHM2.

efficient. If the SD exceeds a certain threshold, a handover might be necessary to maintain the desired QoS.

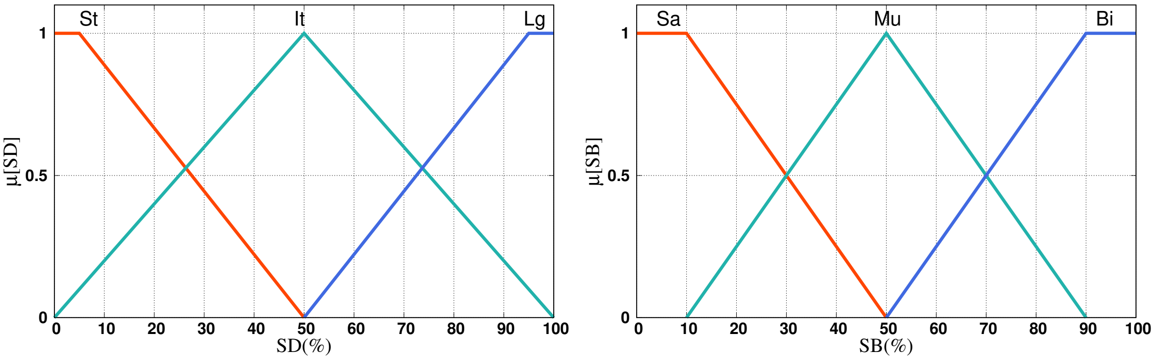
Slice Bandwidth (SB): Bandwidth refers to the data transfer capacity of a slice. A higher bandwidth can accommodate more data, resulting in faster data transfer rates. When the SB is high, it indicates that the slice has ample resources to manage the user's demands, making handovers less likely. Conversely, if the bandwidth is constrained, it might necessitate a handover to a slice with more available bandwidth.

Slice Stability (SS): Stability is a crucial parameter as it dictates the reliability of a network slice. A highly stable slice ensures consistent communication without frequent drops or interruptions. If a user is on a slice with low stability, they might experience disruptions. In such cases, a handover to a more stable slice becomes imperative to ensure a continuous and reliable service.

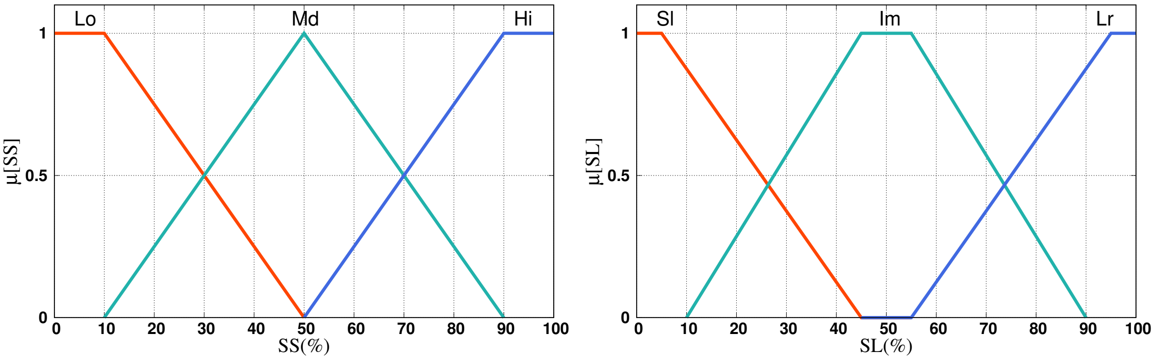
Slice Load (SL): This parameter signifies how occupied the resources of a slice are. When numerous users are active on a slice, its resources can become stretched, leading to potential service degradation. A heavily loaded slice might not offer optimal QoS, prompting a handover to another slice with more available resources.

Handover Decision (HD): Handover in telecommunications refers to the process by which a user's connection is transferred from one network slice or cell to another, without interruption in the ongoing service. This process is pivotal in ensuring seamless user experience, especially in mobile networks as users move geographically or as network conditions change.

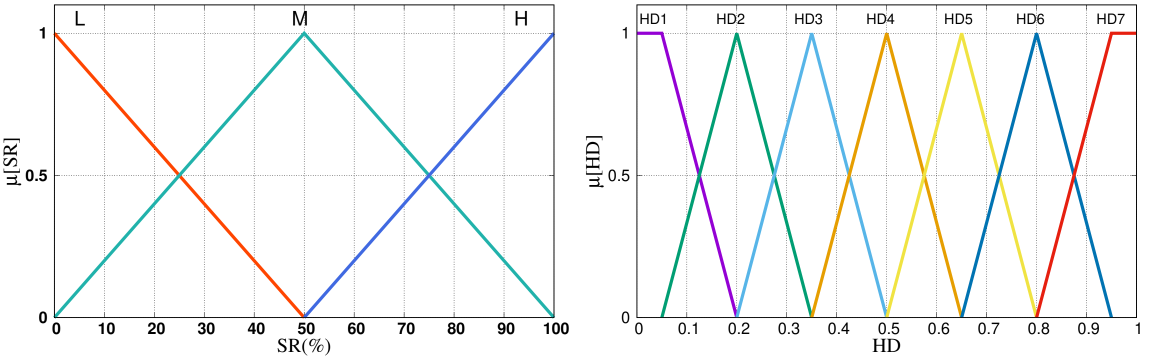
Fig. 8.13 shows the membership functions. In order to easily fuzzify them and be flexible in applying in any scenario, the values for Slice Delay, Bandwidth, Stability and Load are considered between 0 and 100%. So, for example, when we want to use the proposed system in Massive IoT scenario, we can consider the maximum slice delay value 10 ms (100%). But, when applying in Critical Communications,



(a) Slice Delay (b) Slice Bandwidth



(c) Slice Stability (d) Slice Load



(e) Slice Reliability (f) Handover Decision

FIGURE 8.13: Membership functions for FHM1, FHM2 and FHM3.

TABLE 8.12: Parameter and their term sets for FHM1 and FHM2.

Parameters	Term Sets
Slice Delay (SD)	Short (St), Intermediate (It), Long(Lg)
Slice Bandwidth (SB)	Small (Sa), Medium (Mu), Big (Bi)
Slice Stability (SS)	Low (Lo), Medium (Md), High (Hi)
Slice Load (SL)	Small (Sl), Intermediate (Im), Large (Lr)
Handover Decision (HD)	HD1, HD2, HD3, HD4, HD5, HD6, HD7

TABLE 8.13: FRB for FHM1.

Rule	SD	SB	SS	HD
1	St	Sa	Lo	HD5
2	St	Sa	Md	HD4
3	St	Sa	Hi	HD3
4	St	Mu	Lo	HD4
5	St	Mu	Md	HD3
6	St	Mu	Hi	HD2
7	St	Bi	Lo	HD3
8	St	Bi	Md	HD2
9	St	Bi	Hi	HD1
10	It	Sa	Lo	HD6
11	It	Sa	Md	HD5
12	It	Sa	Hi	HD4
13	It	Mu	Lo	HD5
14	It	Mu	Md	HD4
15	It	Mu	Hi	HD3
16	It	Bi	Lo	HD4
17	It	Bi	Md	HD3
18	It	Bi	Hi	HD2
19	Lg	Sa	Lo	HD7
20	Lg	Sa	Md	HD6
21	Lg	Sa	Hi	HD5
22	Lg	Mu	Lo	HD6
23	Lg	Mu	Md	HD5
24	Lg	Mu	Hi	HD4
25	Lg	Bi	Lo	HD5
26	Lg	Bi	Md	HD4
27	Lg	Bi	Hi	HD3

we can consider the maximum slice delay value 1 ms or 5 ms depending on delay sensitivity [102]

TABLE 8.14: FRB for FHM2.

Rule	SD	SB	SS	SL	HD	Rule	SD	SB	SS	SL	HD
1	St	Sa	Lo	Sl	HD4	41	It	Mu	Md	Im	HD4
2	St	Sa	Lo	Im	HD5	42	It	Mu	Md	Lr	HD5
3	St	Sa	Lo	Lr	HD6	43	It	Mu	Hi	Sl	HD2
4	St	Sa	Md	Sl	HD3	44	It	Mu	Hi	Im	HD3
5	St	Sa	Md	Im	HD4	45	It	Mu	Hi	Lr	HD4
6	St	Sa	Md	Lr	HD5	46	It	Bi	Lo	Sl	HD3
7	St	Sa	Hi	Sl	HD2	47	It	Bi	Lo	Im	HD4
8	St	Sa	Hi	Im	HD3	48	It	Bi	Lo	Lr	HD5
9	St	Sa	Hi	Lr	HD4	49	It	Bi	Md	Sl	HD2
10	St	Mu	Lo	Sl	HD3	50	It	Bi	Md	Im	HD3
11	St	Mu	Lo	Im	HD4	51	It	Bi	Md	Lr	HD4
12	St	Mu	Lo	Lr	HD5	52	It	Bi	Hi	Sl	HD1
13	St	Mu	Md	Sl	HD2	53	It	Bi	Hi	Im	HD2
14	St	Mu	Md	Im	HD3	54	It	Bi	Hi	Lr	HD3
15	St	Mu	Md	Lr	HD4	55	Lg	Sa	Lo	Sl	HD6
16	St	Mu	Hi	Sl	HD1	56	Lg	Sa	Lo	Im	HD7
17	St	Mu	Hi	Im	HD2	57	Lg	Sa	Lo	Lr	HD7
18	St	Mu	Hi	Lr	HD3	58	Lg	Sa	Md	Sl	HD5
19	St	Bi	Lo	Sl	HD2	59	Lg	Sa	Md	Im	HD6
20	St	Bi	Lo	Im	HD3	60	Lg	Sa	Md	Lr	HD7
21	St	Bi	Lo	Lr	HD4	61	Lg	Sa	Hi	Sl	HD4
22	St	Bi	Md	Sl	HD1	62	Lg	Sa	Hi	Im	HD5
23	St	Bi	Md	Im	HD2	63	Lg	Sa	Hi	Lr	HD6
24	St	Bi	Md	Lr	HD3	64	Lg	Mu	Lo	Sl	HD5
25	St	Bi	Hi	Sl	HD1	65	Lg	Mu	Lo	Im	HD6
26	St	Bi	Hi	Im	HD1	66	Lg	Mu	Lo	Lr	HD7
27	St	Bi	Hi	Lr	HD2	67	Lg	Mu	Md	Sl	HD4
28	It	Sa	Lo	Sl	HD5	68	Lg	Mu	Md	Im	HD5
29	It	Sa	Lo	Im	HD6	69	Lg	Mu	Md	Lr	HD6
30	It	Sa	Lo	Lr	HD7	70	Lg	Mu	Hi	Sl	HD3
31	It	Sa	Md	Sl	HD4	71	Lg	Mu	Hi	Im	HD4
32	It	Sa	Md	Im	HD5	72	Lg	Mu	Hi	Lr	HD5
33	It	Sa	Md	Lr	HD6	73	Lg	Bi	Lo	Sl	HD4
34	It	Sa	Hi	Sl	HD3	74	Lg	Bi	Lo	Im	HD5
35	It	Sa	Hi	Im	HD4	75	Lg	Bi	Lo	Lr	HD6
36	It	Sa	Hi	Lr	HD5	76	Lg	Bi	Md	Sl	HD3
37	It	Mu	Lo	Sl	HD4	77	Lg	Bi	Md	Im	HD4
38	It	Mu	Lo	Im	HD5	78	Lg	Bi	Md	Lr	HD5
39	It	Mu	Lo	Lr	HD6	79	Lg	Bi	Hi	Sl	HD2
40	It	Mu	Md	Sl	HD3	80	Lg	Bi	Hi	Im	HD3
						81	Lg	Bi	Hi	Lr	HD4

The input parameters and their term sets are shown in Table 8.12.

$$\begin{aligned}
T(SD) &= Short\ (St), Intermediate\ (It), Long\ (Lg)\\
T(SB) &= Small\ (Sa), Medium\ (Mu), Big\ (Bi)\\
T(SS) &= Low\ (Lo), Medium\ (Md), High\ (Hi)\\
T(SL) &= Small\ (Sl), Intermediate\ (Im), Large\ (Lr)
\end{aligned}$$

The membership function for input parameters are defined as follows.

$$\begin{aligned}
\mu_{St}(SD) &= g(SD; St_0, St_1, St_{w0}, St_{w1})\\
\mu_{It}(SD) &= f(SD; It_0, It_{w0}, It_{w1})\\
\mu_{Lg}(SD) &= g(SD; Lg_0, Lg_1, Lg_{w0}, Lg_{w1})\\
\mu_{Sa}(SB) &= g(SB; Sa_0, Sa_1, Sa_{w0}, Sa_{w1})\\
\mu_{Mu}(SB) &= f(SB; Mu_0, Mu_{w0}, Mu_{w1})\\
\mu_{Bi}(SB) &= g(SB; Bi_0, Bi_1, Bi_{w0}, Bi_{w1})\\
\mu_{Lo}(SS) &= g(SS; Lo_0, Lo_1, Lo_{w0}, Lo_{w1})\\
\mu_{Md}(SS) &= f(SS; Md_0, Md_{w0}, Md_{w1})\\
\mu_{Hi}(SS) &= g(SS; Hi_0, Hi_1, Hi_{w0}, Hi_{w1})\\
\mu_{Sl}(SL) &= g(SL; Sl_0, Sl_1, Sl_{w0}, Sl_{w1})\\
\mu_{Im}(SL) &= f(SL; Im_0, Im_{w0}, Im_{w1})\\
\mu_{Lr}(SL) &= g(SL; Lr_0, Lr_1, Lr_{w0}, Lr_{w1})
\end{aligned}$$

The output linguistic parameter is Handover Decision (HD). The term set for HD is defined as follows.

$$HD = \begin{pmatrix} Handover\ Decision\ L1\\ Handover\ Decision\ L2\\ Handover\ Decision\ L3\\ Handover\ Decision\ L4\\ Handover\ Decision\ L5\\ Handover\ Decision\ L6\\ Handover\ Decision\ L7 \end{pmatrix} = \begin{pmatrix} HD1\\ HD2\\ HD3\\ HD4\\ HD5\\ HD6\\ HD7 \end{pmatrix}$$

The membership functions for HD are defined as follows.

$$\begin{aligned}
\mu_{HD1}(HD) &= g(HD; HD1_0, HD1_1, HD1_{w0}, HD1_{w1})\\
\mu_{HD2}(HD) &= f(HD; HD2_0, HD2_{w0}, HD2_{w1})\\
\mu_{HD3}(HD) &= f(HD; HD3_0, HD3_{w0}, HD3_{w1})
\end{aligned}$$

$$
\begin{aligned}
\mu_{HD4}(HD) &= f(HD; HD4_0, HD4_{w0}, HD4_{w1}) \\
\mu_{HD5}(HD) &= f(HD; HD5_0, HD5_{w0}, HD5_{w1}) \\
\mu_{HD6}(HD) &= f(HD; HD6_0, HD6_{w0}, HD6_{w1}) \\
\mu_{HD7}(HD) &= g(HD; HD7_0, HD7_1, HD7_{w0}, HD7_{w1})
\end{aligned}
$$

The FRB for FHM1 and FHM2 is shown in Table 8.13 and Table 8.14, respectively. The FRB is formed by a fuzzy set of dimensions ($|T(HD|) = |T(SD)| \times |T(SB)| \times |T(SS)| \times |T(SL)|$), where ∣T(x)∣ is the number of terms on T(x). The control rules have the form: IF "condition" THEN "control action". For example, for Rule 50 of FBHM2: "IF SD is It, SB is Bi, SS is Md and SL is Im, THEN HD is HD3".

FHM3: Considering Slice Reliability (SR) as a new parameter

We propose a FHM3 considering four parameters: SD, SB, SS and Slice Reliability (SR) as a new parameter.

Slice Reliability (SR): The reliability of a slice refers to its ability to consistently provide the level of service it's designed for without interruptions or degradations. Reliability encompasses various factors including, but not limited to, uptime, consistent performance, and the resilience of the slice in the face of network issues or failures. When a slice has low reliability, the user will be switched to other slices with higher reliability.

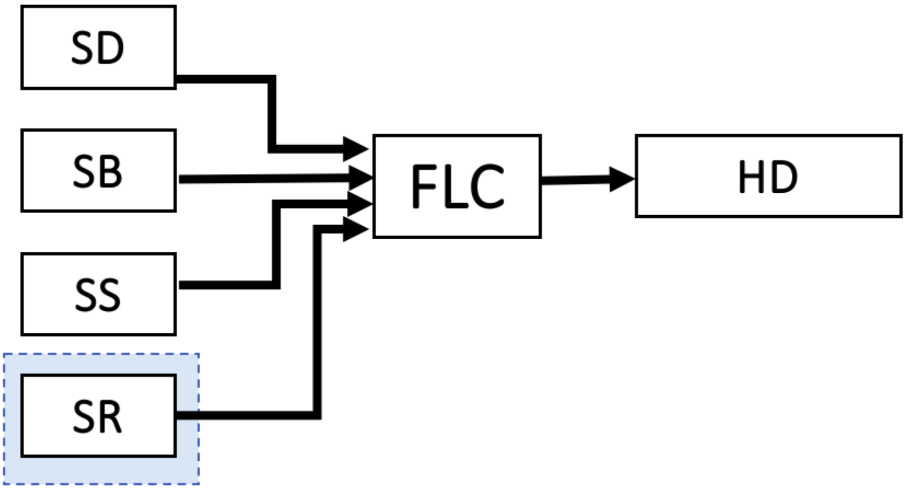


FIGURE 8.14: Proposed system structures for FHM3.

TABLE 8.15: FRB for FHM3.

Rule	SD	SB	SS	SR	HD	Rule	SD	SB	SS	SR	HD
1	Lo	Sm	Lw	L	HD6	41	Me	In	Md	M	HD4
2	Lo	Sm	Lw	M	HD5	42	Me	In	Md	H	HD3
3	Lo	Sm	Lw	H	HD4	43	Me	In	Hg	L	HD4
4	Lo	Sm	Md	L	HD5	44	Me	In	Hg	M	HD3
5	Lo	Sm	Md	M	HD4	45	Me	In	Hg	H	HD2
6	Lo	Sm	Md	H	HD3	46	Me	Bi	Lw	L	HD5
7	Lo	Sm	Md	L	HD4	47	Me	Bi	Lw	M	HD4
8	Lo	Sm	Hg	M	HD3	48	Me	Bi	Lw	H	HD3
9	Lo	Sm	Hg	H	HD2	49	Me	Bi	Md	L	HD4
10	Lo	In	Lw	L	HD5	50	Me	Bi	Md	M	HD3
11	Lo	In	Lw	M	HD4	51	Me	Bi	Md	H	HD2
12	Lo	In	Lw	H	HD3	52	Me	Bi	Hg	L	HD3
13	Lo	In	Md	L	HD4	53	Me	Bi	Hg	M	HD2
14	Lo	In	Md	M	HD3	54	Me	Bi	Hg	H	HD1
15	Lo	In	Md	H	HD2	55	Hi	Sm	Lw	L	HD7
16	Lo	In	Hg	L	HD3	56	Hi	Sm	Lw	M	HD7
17	Lo	In	Hg	M	HD2	57	Hi	Sm	Lw	H	HD7
18	Lo	In	Hg	H	HD1	58	Hi	Sm	Md	L	HD7
19	Lo	Bi	Lw	L	HD4	59	Hi	Sm	Md	M	HD7
20	Lo	Bi	Lw	M	HD3	60	Hi	Sm	Md	H	HD6
21	Lo	Bi	Lw	H	HD2	61	Hi	Sm	Hg	L	HD7
22	Lo	Bi	Md	L	HD3	62	Hi	Sm	Hg	M	HD6
23	Lo	Bi	Md	M	HD2	63	Hi	Sm	Hg	H	HD5
24	Lo	Bi	Md	H	HD1	64	Hi	In	Lw	L	HD7
25	Lo	Bi	Hg	L	HD2	65	Hi	In	Lw	M	HD7
26	Lo	Bi	Hg	M	HD1	66	Hi	In	Lw	H	HD6
27	Lo	Bi	Hg	H	HD1	67	Hi	In	Md	L	HD7
28	Me	Sm	Lw	L	HD7	68	Hi	In	Md	M	HD6
29	Me	Sm	Lw	M	HD6	69	Hi	In	Md	H	HD5
30	Me	Sm	Lw	H	HD5	70	Hi	In	Hg	L	HD6
31	Me	Sm	Md	L	HD6	71	Hi	In	Hg	M	HD5
32	Me	Sm	Md	M	HD5	72	Hi	In	Hg	H	HD4
33	Me	Sm	Md	H	HD4	73	Hi	Bi	Lw	L	HD7
34	Me	Sm	Hg	L	HD5	74	Hi	Bi	Lw	M	HD6
35	Me	Sm	Hg	M	HD4	75	Hi	Bi	Lw	H	HD5
36	Me	Sm	Hg	H	HD3	76	Hi	Bi	Md	L	HD6
37	Me	In	Lw	L	HD6	77	Hi	Bi	Md	M	HD5
38	Me	In	Lw	M	HD5	78	Hi	Bi	Md	H	HD4
39	Me	In	Lw	H	HD4	79	Hi	Bi	Hg	L	HD5
40	Me	In	Md	L	HD5	80	Hi	Bi	Hg	M	HD4
						81	Hi	Bi	Hg	H	HD3

TABLE 8.16: Parameter and their term sets for FBHM3.

Parameters	Term Sets
Slice Delay (SD)	Low (Lo), Medium (Me), High (Hi)
Slice Bandwidth (SB)	Small (Sm), Intermediate (In), Big (Bi)
Slice Stability (SS)	Low (Lw), Medium (Md), High (Hg)
Slice Reliability (SR)	Low (L), Medium (M), High (H)
Handover Decision (HD)	HD1, HD2, HD3, HD4, HD5, HD6, HD7

The membership functions for FHM3 are shown in Fig. 8.13. We show parameters and their term sets for FHM3 in Table 8.16. The FRB for FHM3 is shown in Table 8.15 and has 81 rules. The control rules have the form: IF "condition" THEN "control action". For example, for Rule 1:"IF SD is Lo, SB is Sm, SS is Lw and SR is L, THEN HD is HD6".

8.5 FRSM Testbed Design

For implementation of our system, we take into account three input parameters: Coverage (CV), User Priority (UP), and Spectral Efficiency (SE). The output parameter is Radio Access Technology Decision Value (RDV).

In order to evaluate the proposed system, we designed and implemented a testbed as shown in Fig. 8.15. For implementation of our testbed, we will use a Raspberry Pi Model B (Pi4B), which will serve as SDN controller. Another Raspberry Pi4B will operate as User Equipment (UE). While, three additional Raspberry Pis4B which as BSs indicating three Radio Access Technologies (RATs): 5G, 4G, and WiFi. These Raspberry Pis4B has been equipped with 5G, 4G, and WiFi hats, thereby establishing connections to all three RATs and the UE. By this configuration can be collected the pertinent network traffic details from each of the RATs, including crucial metrics such as RSRP (Reference Signal Received Power), RSSI (Received Signal Strength Indicator) and Data Rate (bps). Moreover, the SDN controller can receive the user-related information such as SIM ID and IMEI from the UE Raspberry Pi4B. The FRSS implemented in SDN controller selects the most appropriate RAT based on three input parameters.

The devices used in the testbed prototype 1 are shown in Fig. 8.16. The WiFi information is obtained through a connection to the router. The 4G data are collected via a 4G antenna and a 4G wireless module (The 4GPi LTE Cat.4 Communication Module) attached to the Raspberry Pi. The term "Cat.4" refers to Category 4, which is a classification within the LTE standard. LTE Cat.4 devices support maximum theoretical download speeds of up to 150 Mbps and upload speeds of up to 50 Mbps.

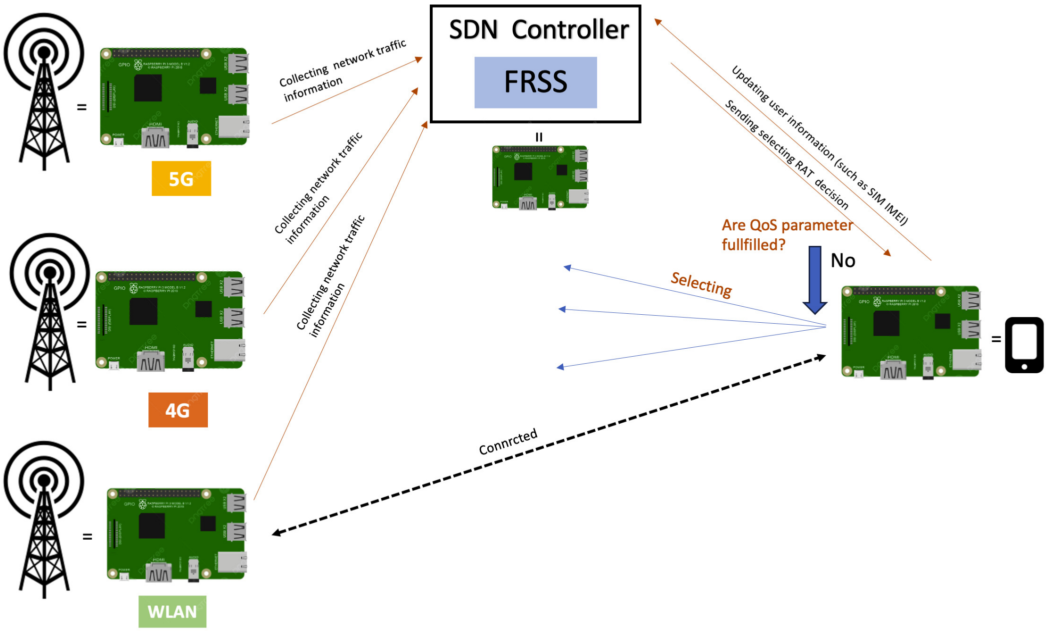


FIGURE 8.15: Testbed structure.

This level of performance is suitable for various applications requiring high-speed internet access [103]. Meanwhile, the 5G information is gathered through Network Simulator 3 (NS-3).

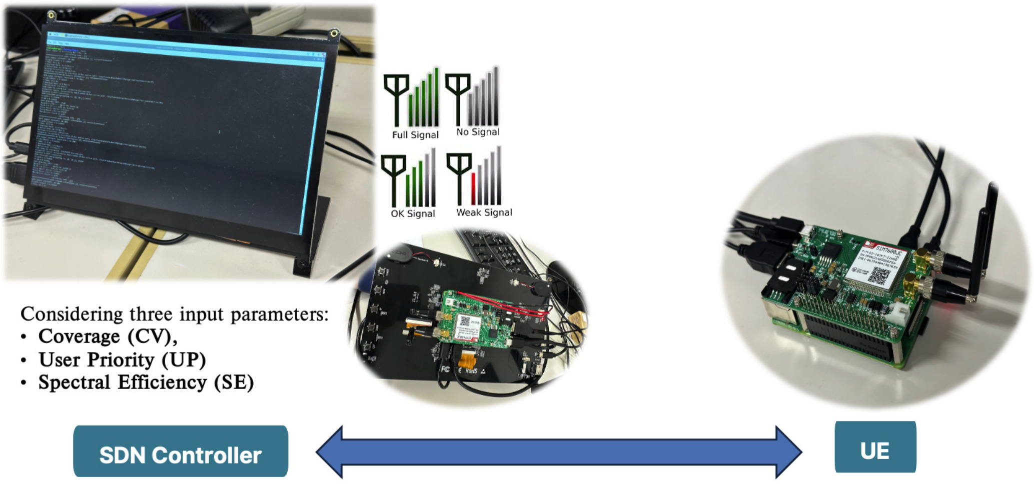


FIGURE 8.16: The testbed prototype 1.

In our testbed, we will describe input and output parameters of the FRSS associated with testbed setup as follows.

Coverage (CV): The CV parameter is a critical factor in assessing the effective range of RAT cell. The CV is determined by considering both the signal strength and RAT-specific signal quality indicators. This parameter varies across different RATs, reflecting their unique characteristics and operational environments.

- **5G** utilizes a wide spectrum that includes high, mid, and low frequency bands. The coverage range of 5G cells varies significantly depending on the used frequency band. Higher frequencies offer greater capacity but shorter range, while lower frequencies provide broader coverage.
- **4G** offers a good coverage and range, especially in low frequency bands. They provide reliable connectivity over relatively larger areas.
- **Wi-Fi** provides coverage within a limited area. It is well-suited for indoor use such as homes, offices, public spaces and offers high-speed wireless connectivity.

In our testbed setup, the CV is determined by RAT signal strength. For 5G and 4G networks, we measure the signal strength using the RSRP metric, while for Wi-Fi networks we employ the RSSI value.

User Priority (UP): The UP is a crucial parameter in our system that reflects the relative importance of users or devices. A higher UP means that the system prioritizes finding a RAT that can offer better QoS.

In our testbed, the UP value is determined by considering factors such as the specific applications used by the user and the current data pricing models.

Spectral Efficiency (SE): The SE measures the efficiency of spectrum use, calculated as the number of bits transmitted per second per Hertz (bps/Hz). It indicates the data transmission rate possible within a given bandwidth, showcasing the effectiveness of spectrum utilization. SE is calculated using the following equation:

$$SE = \frac{ADR(bps)}{AB(Hz)},$$

where ADR represents Achievable Data Rate, which depends on factors like the modulation technique, bits per symbol, and so on. The AB stands for the Available Bandwidth. The computation of SE considers factors such as channel conditions such as Signal-to-Noise Ratio (SNR), modulation, coding schemes, and other elements pertinent to the communication system being analyzed.

Radio Access Technology Decision Value (RDV): The RDV is the output value, which provides a quantitative measure for selecting the most appropriate RAT.

Chapter 9

Evaluation Results

In this chapter, we present the performance of the proposed system for different parameters.

9.1 Result of FRSM

9.1.1 Result of FRSM1 Considering CV, UP and SE

The simulation results for FRSM1 are shown in Fig. 9.1. They present the relation of RDV with SE for various UE values considering CV as a constant parameter.

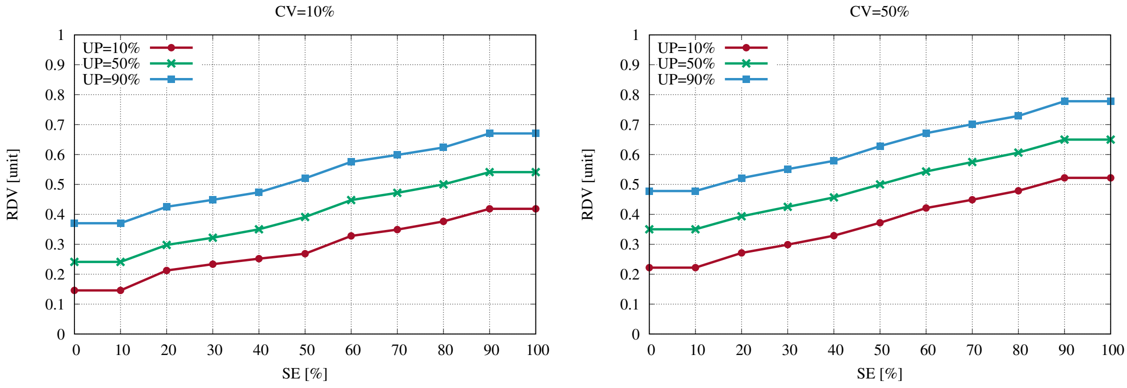
In Fig. 9.1(a), we consider the CV value 10%. When SE is increased from 20% to 40% and 40% to 80% for UP 90%, we see that RDV is increased by 5% and 15%, respectively. When the RAT has a high transmission bandwidth, the RAT decision value will be higher. When we increased the UP value from 10% to 50% and 50% to 90%, both RDV values are increased by 12% when SE is 80%. This indicates that when the user′s priority is high, the user has a high possibility of selecting and connecting with a RAT that has better QoS.

We compare Fig. 9.1(a) with Fig. 9.1(b) to see the effect of CV to RDV. We change the CV value from 10% to 50%. The RDV is increased by 11% when the UP value is 50% and the SE is 50%. When the RAT has better signal coverage, the RAT decision value also is higher.

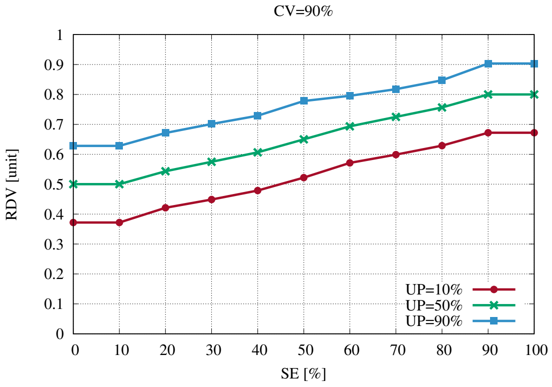
We increase the value of CV to 90% in Fig. 9.1(c). Comparing the results with Fig. 9.1(a) and Fig. 9.1(b), we can see that the RDV values have been increased significantly. All RDV values for UP 50% and 90% are greater than 0.5. Thus, there is a high probability that the user will select a better RAT with good coverage and bandwidth for satisfying user requirements.

9.1.2 Result of FRSM2 Considering CV, UP, SE and RL

The simulation results for FRSM2 are shown in Fig. 9.2, Fig. 9.3 and Fig. 9.4. In Fig. 9.2 (a), with CV and UP values considered 10%, we found that all RDV values for



(a) SB=10% (b) SB=50%



(c) SB=90%

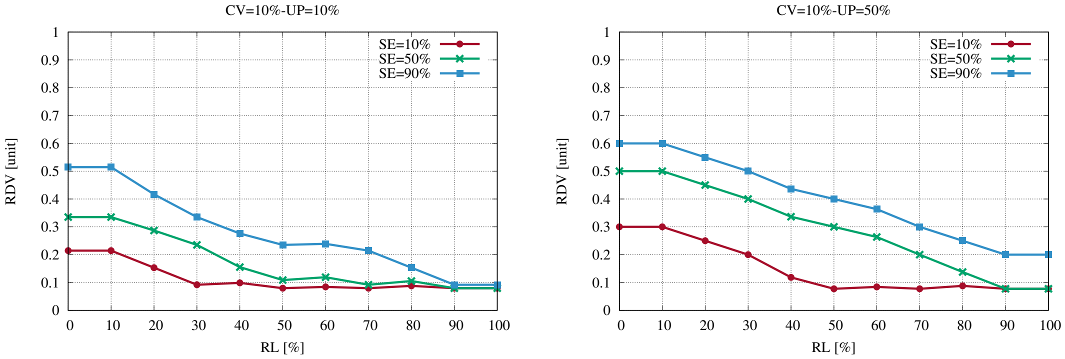
FIGURE 9.1: Simulation results for FRSM1.

different UP and RL values are less than 0.5. This indicates that when the coverage area is small and the user priority is low, the probability of selecting RAT is decreased, even if the RAT has a low load and high transmission bandwidth. When comparing Fig. 9.2 (a), Fig. 9.2 (b) and Fig. 9.2 (c), we notice that RDV values increase as UP is raised to 50% and 90% repectively. A higher UP value implies that the system selects a RAT that offers a better QoS for that user or device. RATs with superior performance characteristics will be selected to ensure an enhanced user experience.

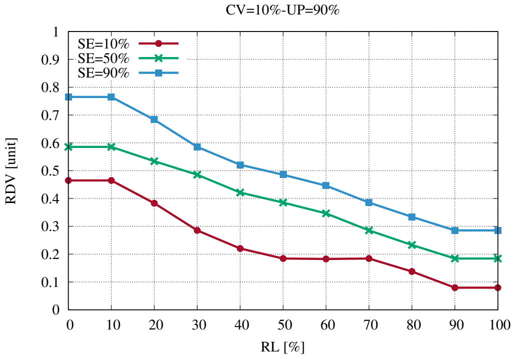
When the RAT has enhanced signal coverage, as indicated by changing the CV parameter from 10% to 50%, there is a significant increase in the RDV values. This effect is observed when comparing Fig. 9.2 (a) and Fig. 9.3 (a) (UP is 10%), the RDV increases by 20% when SE is 50% and RL is 20%. Also, comparing Fig. 9.2 (b) Fig. 9.3 (b) (UP is 50%) and Fig. 9.2 (c) Fig. 9.3 (c) (UP is 90%), the RDV increases by 20% for both cases. This indicates that RATs with wide coverage areas have a high possibility of being selected. The wide coverage area will have good QoS, making the RAT better option for connection.

When we increase the SE value from 10% to 50% and from 50% to 90% (See Fig. 9.3 (a)), we note that the RDV increases by 20% and 18% respectively, for UP are 10% and RL 10%. For the same case, When we change UP value from 10% to 50% and 50% to 90% (See Fig. 9.3 (b) (UP 50%) and Fig. 9.3 (c) (UP 90%)), The RDV increases by 20% and 10%, respectively for UP 50% and RL 10% and the RDV both increases by 12%, respectively for UP 90% and RL 10%. This implies that the RAT decision value tends to be higher when the RAT offers wide transmission bandwidth and better network capacity, even when there is a difference in user priority.

By increasing the value of CV to 90% as shown in Fig. 9.4. We compared with Fig. 9.2 and Fig. 9.3, RDV values are higher. In Fig. 9.4 (a) and Fig. 9.4 (b), when we changed the RL values, we can see the RDV values are decreasing significantly. In Fig. 9.4 (c), when RL is increased from 10% to 50% and then from 50% to 90%, RDV values decrease by 13% and 12% respectively, when SE is 50%. This indicates that RATs with low load and better coverage and bandwidth will be selected.

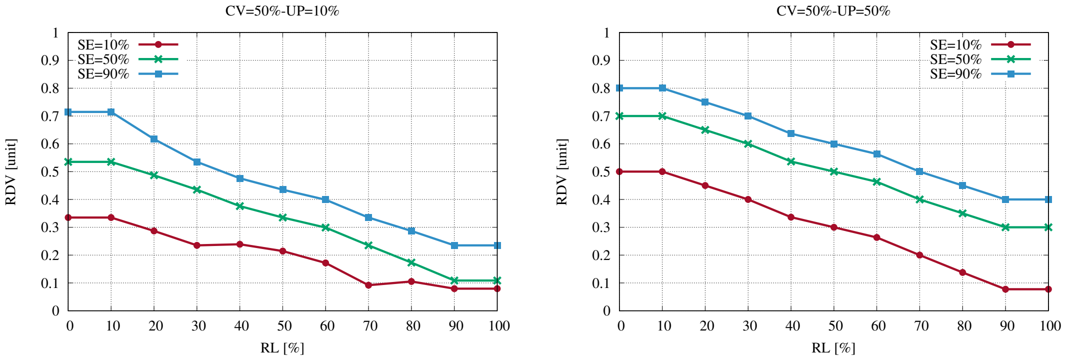


(a) UP=10% (b) UP=10%

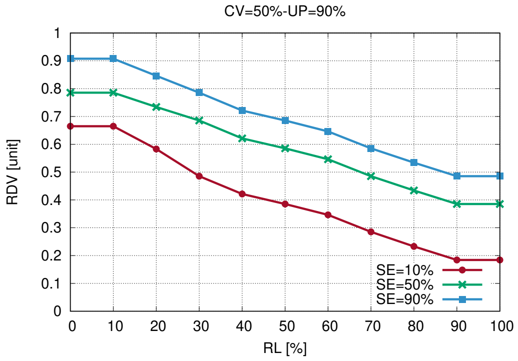


(c) UP=90%

FIGURE 9.2: Simulation results for FRSM2 (CV=10%).

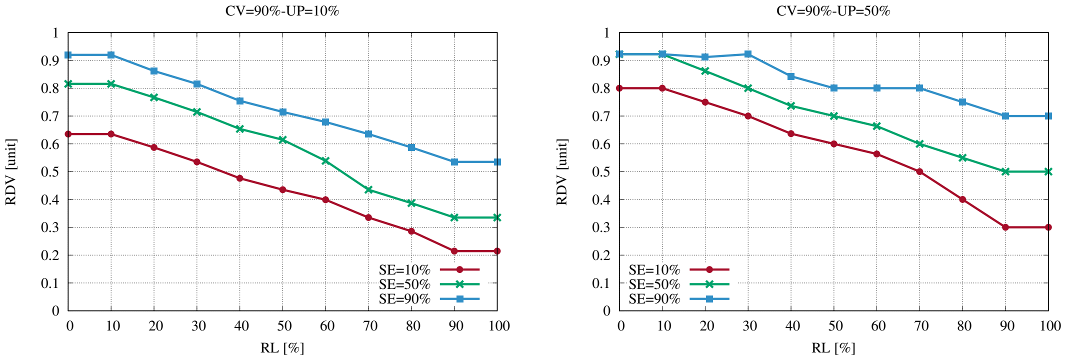


(a) UP=10% (b) UP=50%

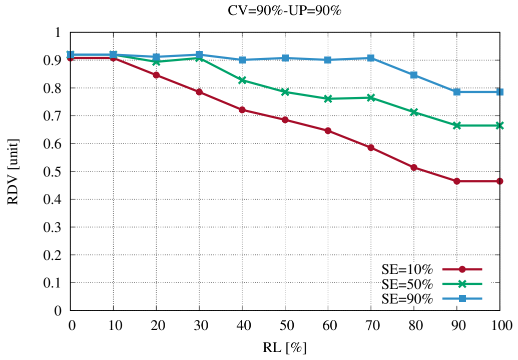


(c) UP=90%

FIGURE 9.3: Simulation results for FRSM2 (CV=50%).



(a) UP=10% (b) SB=50%



(c) UP=90%

FIGURE 9.4: Simulation results for FRSM2 (CV=90%).

9.1.3 Result of FRSM3 Considering CV, UP, SE and QoE

The simulation results for FRSM3 are shown in Fig. 9.5, Fig. 9.6 and Fig. 9.7. They show the relation between RDV and QoE for differing SE values while considering both CV and UP as constant parameters.

In Fig. 9.5 (a), the CV value is 10% and UP value is 10%. All RDV values for all UP and QoE are less than 0.5. In Fig. 9.5 (b) and Fig. 9.5 (c), we change the UP value from 10% to 50% and 90%. We see that all RDV values are increasing compared with Fig. 9.5 (a). This shows that a device (user) has a greater probability of selecting and connecting to a RAT that has good QoS.

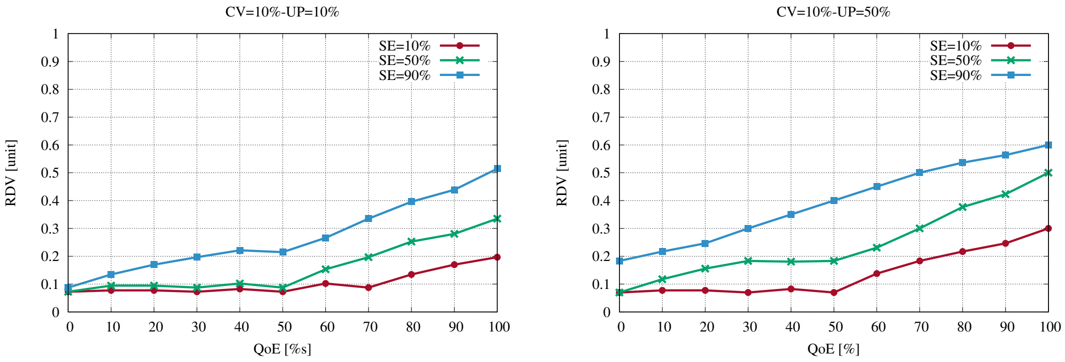
We compare Fig. 9.6 (a) with Fig. 9.5 (a) to see how CV has affected RDV. We change the CV value from 10% to 50%. The RDV is increased by 30% when the UP value is 10%, SE is 90% and QoE is 50%. When the RAT has better network capacity, the user satisfaction value also is higher. The RAT decision value significantly increases when the RAT has enhanced signal coverage. In Fig. 9.6 (b), when we increased the SE from 10% to 50% and 50% to 90%, RDV is increased by 20% and 10% for QoE 50%, respectively. The RAT decision value will be greater if the RAT has a large transmission bandwidth for medium coverage, user priority and QoE. In Fig. 9.6 (c), we see the RDV values are more than 0.5 for SE 90% and all QoE values. That means the RAT with medium coverage and a large transmission bandwidth has a high possibility of being selected when user priority is high.

We increase the value of CV to 90% in Fig. 9.7. Comparing the results with Fig. 9.5 and Fig. 9.6, we can see that the RDV values are higher. In Fig. 9.7 (a), when we increased the QoE value from 10% to 50% and 50% to 90%, RDV values are increased by 15% and 14% when SE is 90%. All RDV values for all UP and QoE are more than 0.5 in Fig. 9.7 (c). This means that the user will select a better RAT with good coverage and bandwidth for satisfying user requirements.

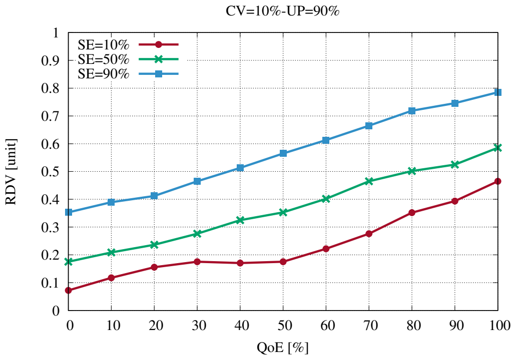
9.1.4 Result of FSQoE1 Considering NC, EEUT and Cn

The simulation results for FSQoE1 are shown in Fig. 9.8(a), Fig. 9.8(b) and Fig. 9.8(c). They show the relation of QoE with Cn for different EEUT values considering NC as a constant parameter.

In Fig. 9.8(a), we consider the NC value 10%. When Cn is increased from 10% to 50% and 50% to 90% for EEUT 90%, we see that QoE is increased by 15% and 12%, respectively. This is because when users have good network connection, the QoE value will be higher. When we increased the EEUT value from 10% to 50% and 50% to 90%, both QoE values are increased by 11% when Cn is 50%. This indicates that when users experience higher throughput, the user satisfaction will be higher.

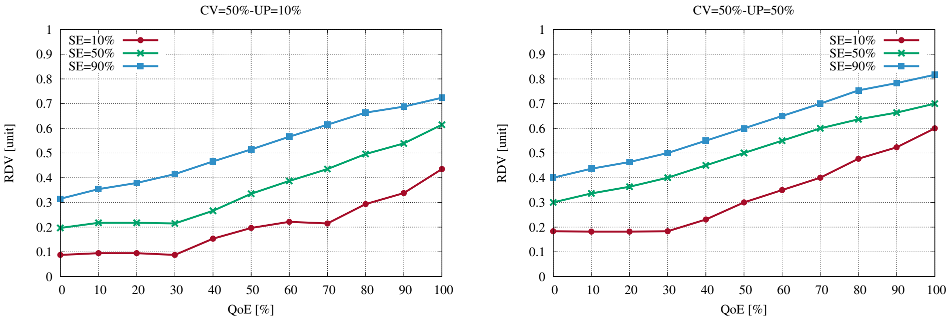


(a) UP=10% (b) UP=50%

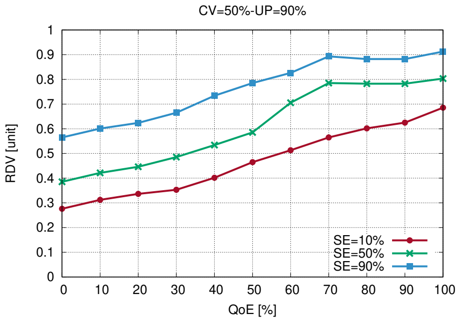


(c) UP=90%

FIGURE 9.5: Simulation results for FRSM3 (CV=10%).

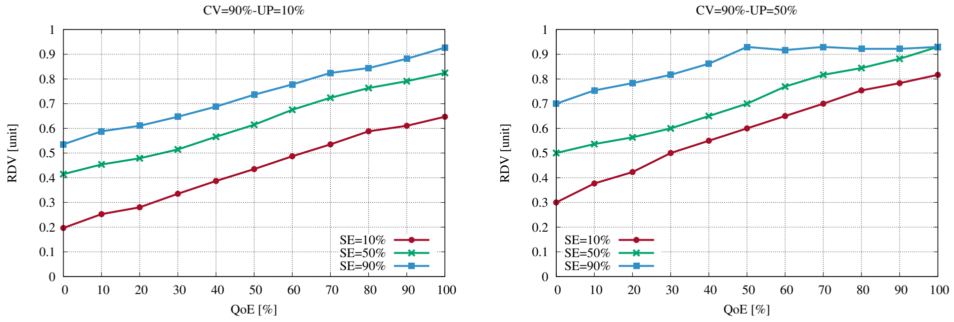


(a) UP=10% (b) UP=50%

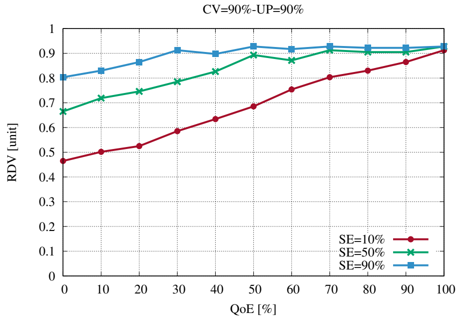


(c) UP=90%

FIGURE 9.6: Simulation results for FRSM3 (CV=50%).



(a) UP=10% (b) UP=50%



(c) UP=90%

FIGURE 9.7: Simulation results for FRSM3 (CV=90%).

We compare Fig. 9.8(a) with Fig. 9.8(b) to see how NC has affected QoE. We change the NC value from 10% to 50%. The QoE is increased by 15% when the EEUT value is 90% and Cn is 90%. When the RAT has better network capacity, the user satisfaction value also is higher.

We increase the value of NC to 90% in Fig. 9.8(c). Comparing the results with Fig. 9.8(a) and Fig. 9.8(b), we can see that the QoE values are increased significantly.

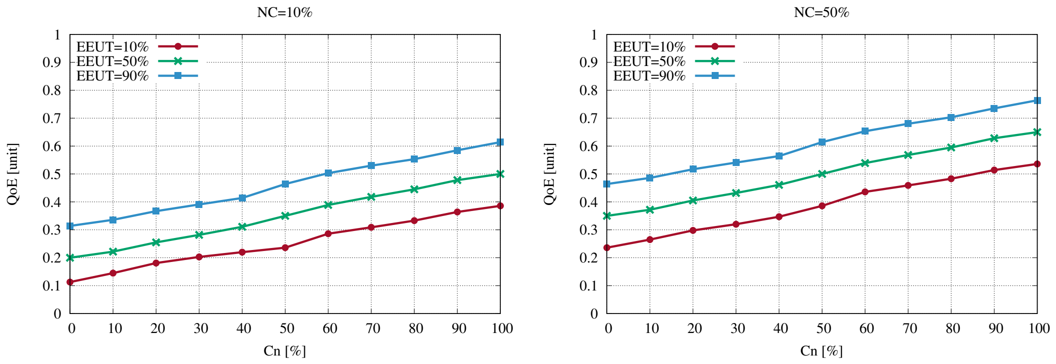
9.1.5 Result of FSQoE2 Considering NC, EEUT, Cn and Se

The simulation results for FSQoE2 are given in Fig. 9.9, Fig. 9.10 and Fig. 9.11. In following, we show the relation between QoE and Se for different Cn values by considering NC and EEUT as a constant parameter.

In Fig. 9.9, we consider NC value 10%. When EEUT is increased from 10% to 50% and 90%, in case when Cn value is 50% and Se value is 50%, as shown in Fig. 9.9(a), Fig. 9.9(b) and Fig. 9.9(c), we see that QoE is increased by 10% and 9%, repectively. This is because when users have higher throughput their satisfaction will be higher. In Fig. 9.9(c), we increased the Cn value from 10% to 50% and 50% to 90%. When Se is 50%, the QoE values are increased by 12% and 18%, respectively. This means that when users connected with a RAT have good connection, the QoE value will be higher.

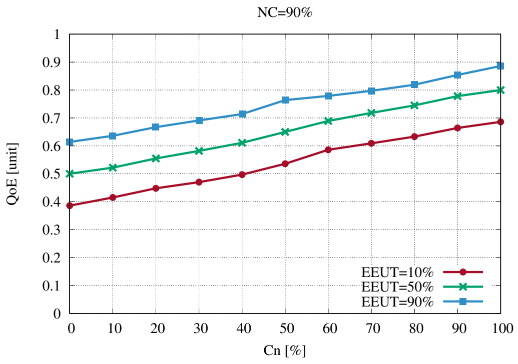
We change NC value from 10% to 50% in Fig. 9.10. We see that the QoE is increased by 27% when the EEUT value is 10%, Cn is 50% and Se is 90%. This indicates that user satisfaction is higher when the RAT has a better traffic volume density giving services to more users. In Fig. 9.10(c), the QoE values are over 0.5 when NC is 50%, EEUT is 90% for all Se values. When the RAT has intermediate network capacity and provides good throughput to users, their satisfaction will be high.

In Fig. 9.11, we consider the scenario of NC is big (90%). Comparing the results with the intermediate NC scenario and the small NC scenario (See Fig. 9.9 and Fig. 9.10), we can see that the QoE values are increased significantly. In Fig. 9.11(a), when we changed Se value from 10% to 70% for Cn is 90%, we see that the QoE value is increased by 29%. When a RAT provides a good network capacity and better security for users even in case of low throughput, users satisfaction will be better. When we compare Fig. 9.11(c) with Fig. 9.10(c) and Fig. 9.9(c), we see that the QoE is increased by 22% and 12% when Cn value is 90% and Se value is 50%, respectively.



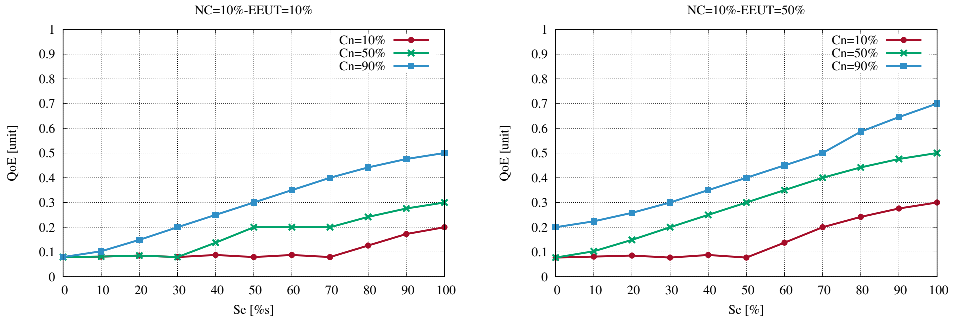
(a) NC=10%

(b) NC=50%



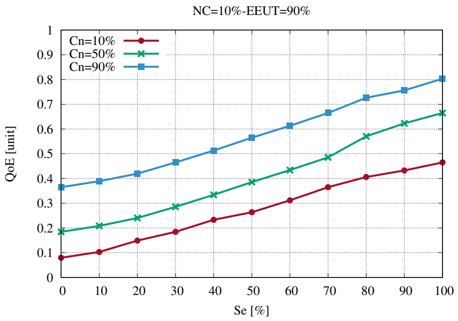
(c) NC=90%

FIGURE 9.8: Simulation results for FSQoE1.



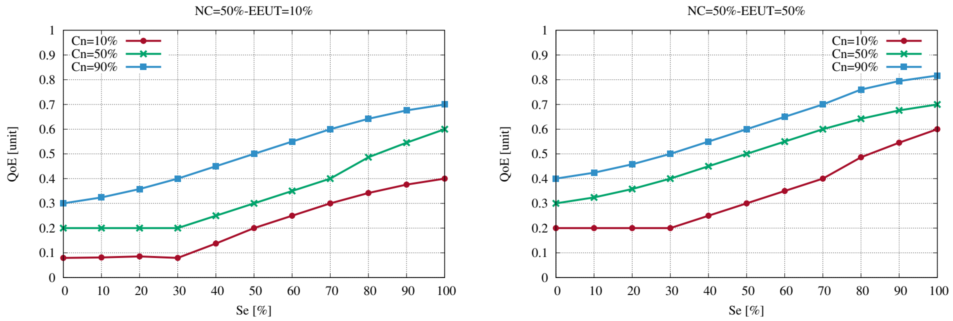
(a) EEUT=10%

(b) EEUT=50%



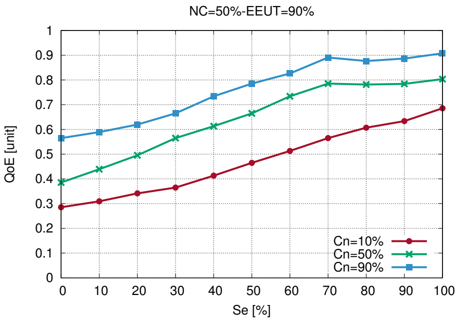
(c) EEUT=90%

FIGURE 9.9: Simulation results for FSQoE2 (NC= 10%).



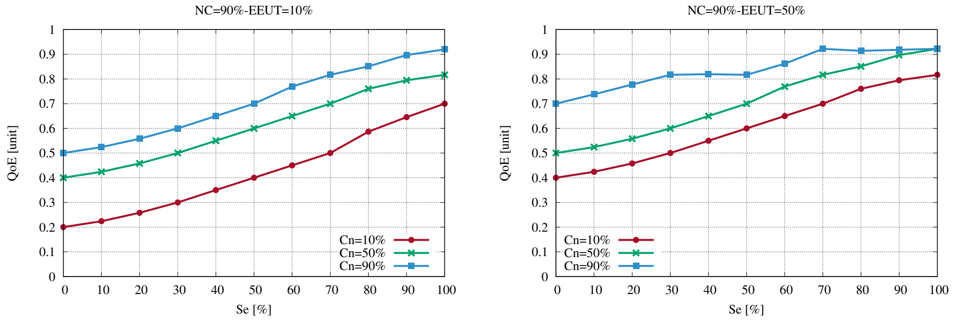
(a) EEUT=10%

(b) EEUT=50%

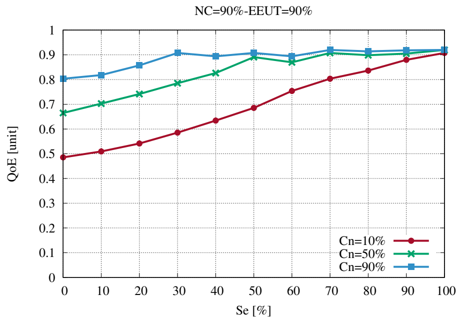


(c) EEUT=90%

FIGURE 9.10: Simulation results for FSQoE2 (NC=50%).



(a) EEUT=10% (b) EEUT=50%



(c) EEUT=90%

FIGURE 9.11: Simulation results for FSQoE2 (NC=90%).

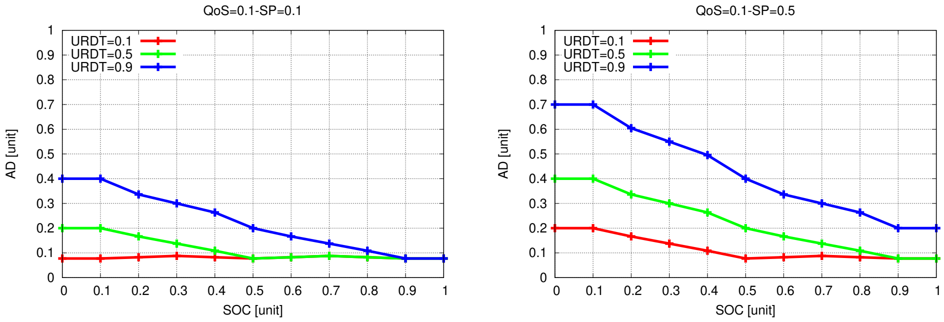
9.2 Result of FACM

The simulation results for FACM are shown in Fig. 9.12, Fig. 9.13, Fig. 9.14, Fig. 9.15 and Fig. 9.16. They show the relation of AD with SOC. We consider URDT, QoS and SP as constant parameters.

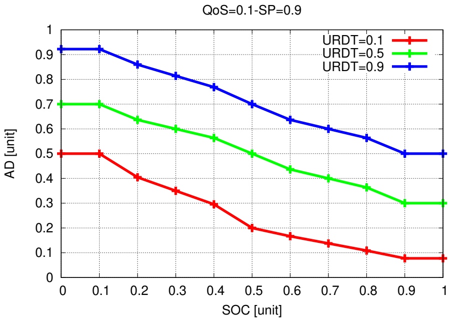
In Fig. 9.12 (a), we consider the QoS value 0.1 and the SP value 0.1. When SOC is increased, we see that AD is decreased. For SOC 0.1, when URDT is increased from 0.1 to 0.5 and 0.5 to 0.9, the AD is increased by 12.25% and 20% respectively. In Fig. 9.12 (b), we increased the SP to 0.5. We see that AD is increased with the increase of the SP value. In Fig. 9.12 (c), when we changed the SOC value from 0.3 to 0.7, the AD is decreasing by 20% when the URDT value is 0.5. This is because a higher SOC value means the slice is more overloaded and the network can't provide the service for a new user.

When we increase QoS value from 0.1 to 0.3 in Fig. 9.12 to Fig. 9.13, the AD values are increased. When the QoS increases from 0.1 to 0.3, the AD increases 20% when SP value is 0.5, SOC value is 0.3 and the URDT value is 0.5. In Fig. 9.14 and Fig. 9.15, we increase QoS value to 0.5 and 0.7 respectively. When SP is 0.5, 0.9 and URDT is 0.9, all AD values are higher than 0.5. This means that the system accepts all requests from new users.

In Fig. 9.16, we increase the value of QoS to 0.9. We see that the AD value is increased much more compared with the other results.

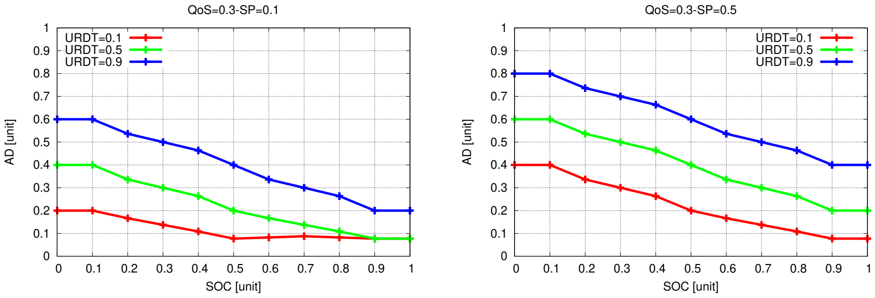


(a) SP=0.1 (b) SP=0.5

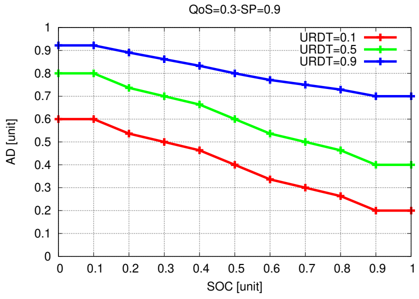


(c) SP=0.9

FIGURE 9.12: Simulation results for FACM (QoS=0.1).

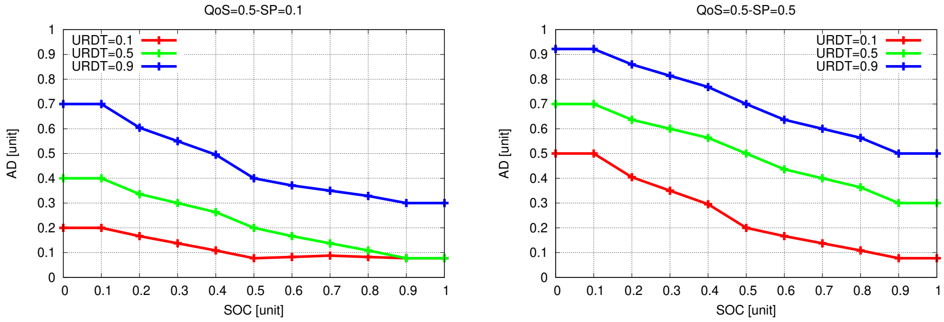


(a) SP=0.1 (b) SP=0.5

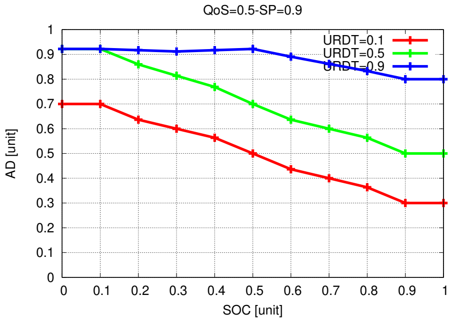


(c) SP=0.9

FIGURE 9.13: Simulation results for FACM (QoS=0.3).

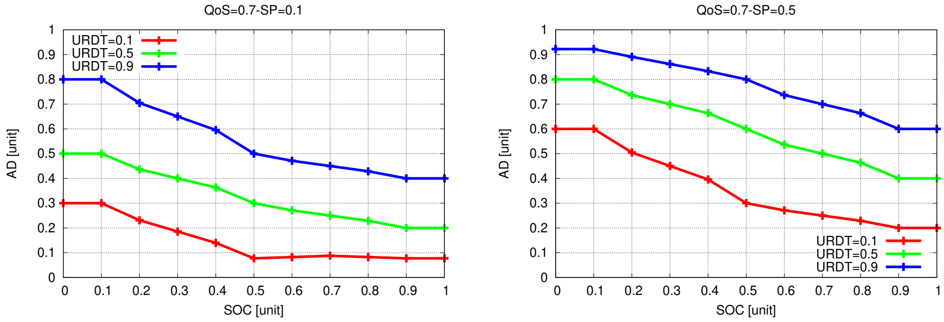


(a) SP=0.1 (b) SP=0.5

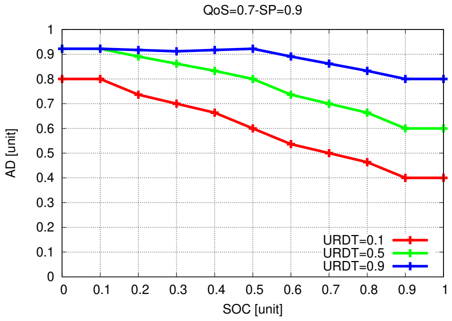


(c) SP=0.9

FIGURE 9.14: Simulation results for FACM (QoS=0.5).

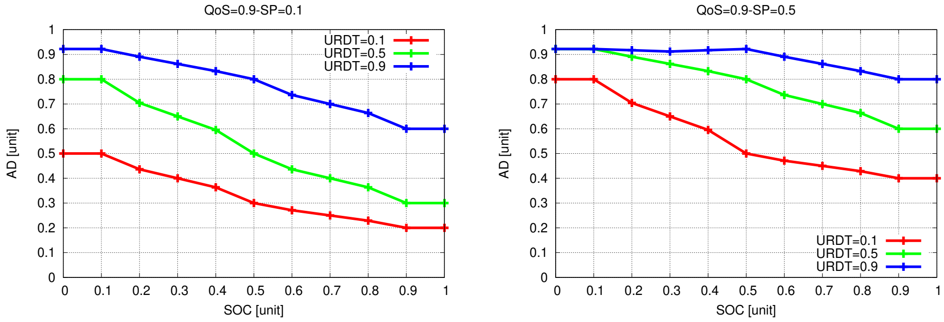


(a) SP=0.1 (b) SP=0.5

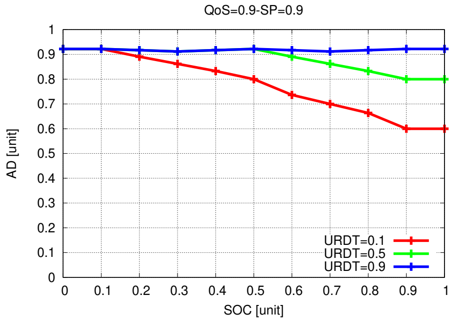


(c) SP=0.9

FIGURE 9.15: Simulation results for FACM (QoS=0.7).



(a) SP=0.1 (b) SP=0.5



(c) SP=0.9

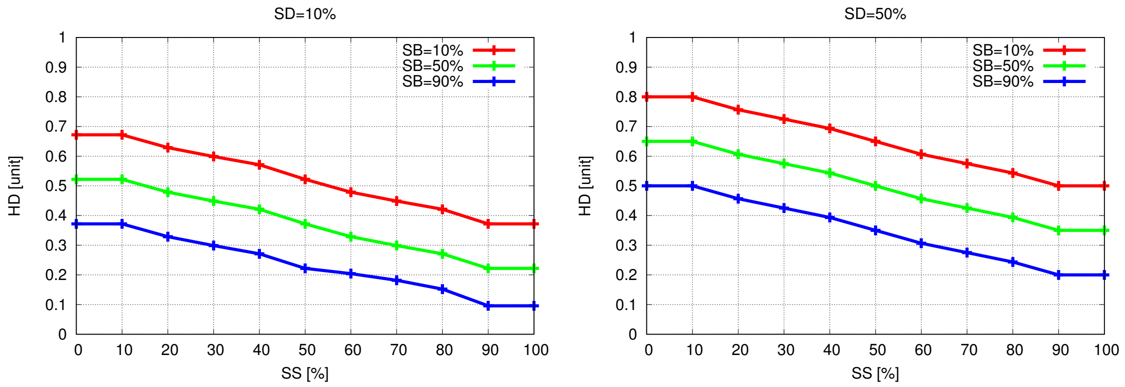
FIGURE 9.16: Simulation results for FACM (QoS=0.9).

9.3 Result of FHM

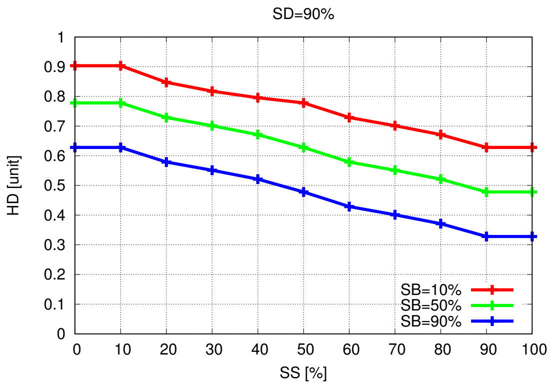
9.3.1 Result of FHM1 Considering SD, SB and SS

The simulation results for FBHM1 are shown in Fig. 9.17. They show the relation between HD and SS for various SB values while considering SD as a constant parameter. In Fig. 9.17(a), we consider the SD value 10%. For SS 50%, when SB is increased from 10% to 50% and 50% to 90%, the HD decreases by 15%, respectively. This means that the probability of handover to other slices is low when the present slice provides the user with more bandwidth.

We change the SD value from 10% to 50% to determine how SD has affected HD. We compare Fig. 9.17(a) with Fig. 9.17(b). When both SB and SS values are 50%, the HD increases by 13%. This is because the handover to another slice is required when the present slice delay is higher. In Fig. 9.17(b), when the SS is increased from 20% to 40% and from 40% to 80% for SD 50% and SB 50%, the HD decreases by 6% and 15%, respectively. As can be seen the HD decreases as SS increases. This indicates that the present slice is more stable, and making handover to other slices is necessary. We increase the SD value in Fig. 9.17(c) to 90%. When we compare the results with Fig. 9.17(a) and Fig. 9.17(b), we can see that the HD values are increased. All HD values are higher than 0.5 for SB value 10%. Thus, the mobile device will switch to a different slice.



(a) SD=10% (b) SD=50%



(c) SD=90%

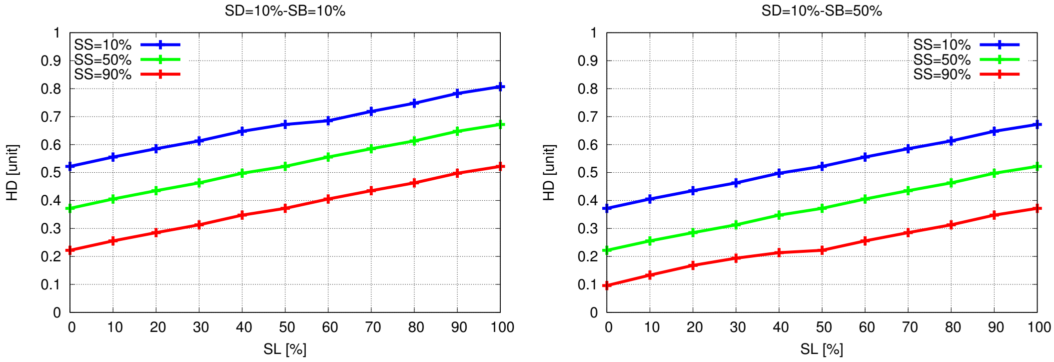
FIGURE 9.17: Simulation results of FHM1

9.3.2 Result of FHM2 Considering SD, SB, SS and SL

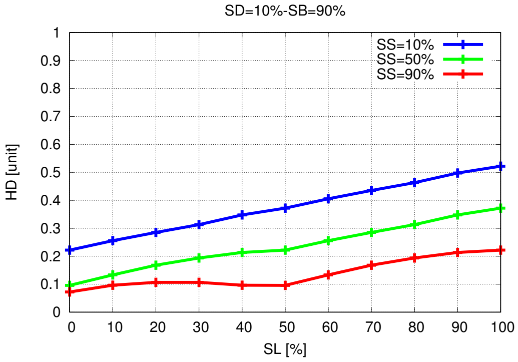
The simulation results for FBHM2 are presented in Fig. 9.18, Fig. 9.19 and Fig. 9.20. We see effect of SL on HD to improve QoS.

In Fig. 9.18(a), we consider the SD value 10%. For SB 10% and SS 10%, when SL is increased from 20% to 40% and 40% to 80%, we see that HD is increased by 6% and 10%, respectively. However, when we increased the SB value from 10% to 50% (see Fig. 9.18(a) and Fig. 9.18(b)) and 50% to 90% (see Fig. 9.18(b) and Fig. 9.18(c)), the HD value is deceased by 15% for both cases when the SS value is 10% and the SL value is 50%. This indicates that when the present slice load is high, the possibility of handover to other slices is high. But, when the present slice has greater bandwidth, the possibility of handover to other slices is low. When the present slice can offer high bandwidth and low delay (see Fig. 9.18(c)), the mobile device stay connected to the present slice.

Fig. 9.19 shows the HD for the moderate slice delay considering different parameters. Comparing the results of Fig. 9.19(a) with Fig. 9.19(b) and Fig. 9.19(c), in case when SL is 50%, SS is 50% and we increased the SB value from 10% to 50% and 50% to 90%, the HD value is decreased by 15% for both cases. In Fig. 9.19(a), we see that



(a) SB=10% (b) SB=50%



(c) SB=90%

FIGURE 9.18: Simulation results for FHM2 (SD=10%).

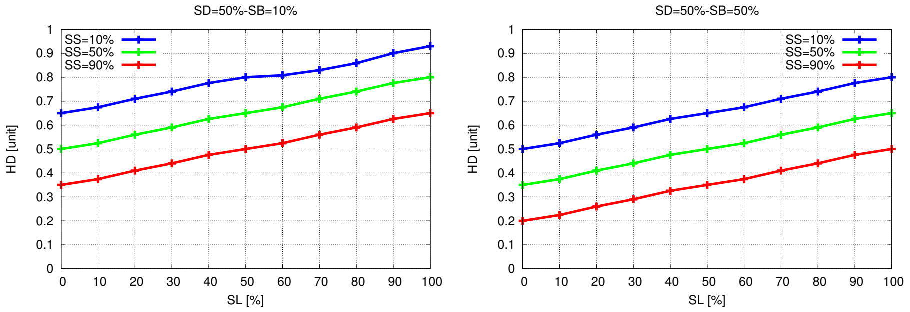
all HD values are greater than 0.5 when SS is 10% and SS is 50%. Thus, the mobile device will make a handover to another slice. But, the mobile device connected with the present slice with high bandwidth will not make a handover except the case when the present slice has a higher load and less stability (see Fig. 9.19(b) and Fig. 9.19(c)).

Comparing the results of Fig. 9.20(a) with other results, we can see that HD values have increased significantly. All HD values are greater than 0.5 for SD 90%, SB 10%, and SS values of 10% and 50%. As a result, the mobile device will handover to another slice for better QoS. In Fig. 9.20(b) and Fig. 9.20(c), with the increase of SB, we can see that the possibility of handover will decrease even if the delay is high.

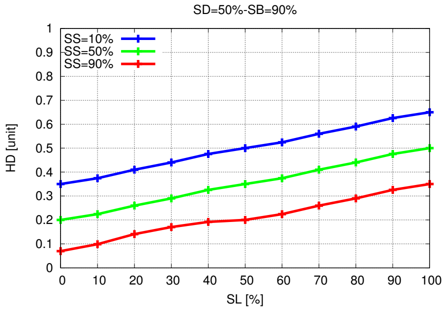
9.3.3 Result of FHM3 Considering SD, SB, SS and SR

The simulation results are shown in Fig. 9.21, Fig. 9.22 and Fig. 9.23. They show the relation of HD with SR for different SS values considering SD and SB as constant parameters.

In Fig. 9.21, we consider the SD value 0.1 ms. For SB 10% and SS 10% (See Fig. 9.21 (a)), when SR is increased from 10% to 60% and 60% to 90%, we see that HD is decreased by 15% and 8%, respectively. But, when we increased the SS value

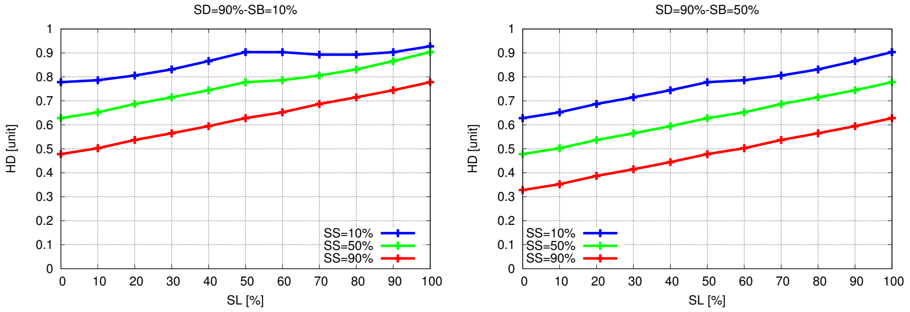


(a) SB=10% (b) SB=50%

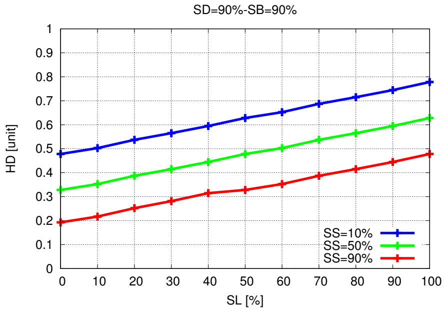


(c) SB=90%

FIGURE 9.19: Simulation results for FHM2 (SD=50%).



(a) SB=10% (b) SB=50%



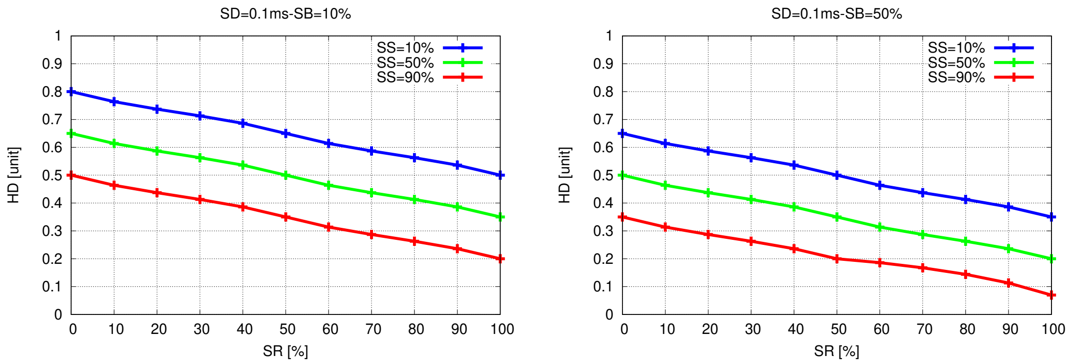
(c) SB=90%

FIGURE 9.20: Simulation results for FHM2 (SD=90%).

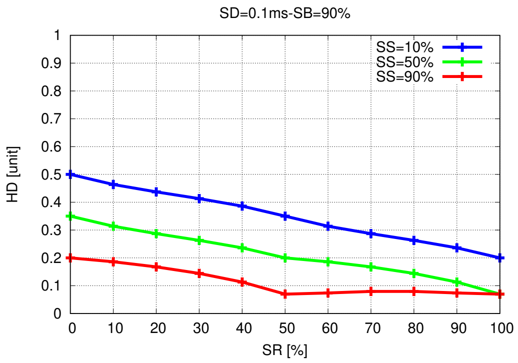
from 10% to 90%, the HD value is deceased by 30% when the SR value is 50%. This is because the present slice is more stable and the handover possibility to the other slices is low. When we increased the SB value from 10% to 50% and 90% (See Fig. 9.21 (b) and Fig. 9.21 (c)), the HD value is deceased by 15% when the SS value is 10% and the SR value is 60% for both cases. This indicates that when the present slice is heavily loaded, the chance of handover to the other slices is high, whereas the chance of handover to the other slices is low when the present slice has more bandwidth.

We compare Fig. 9.21 with Fig. 9.22 to see how SD has affected HD. We change the SD value from 0.1 ms to 0.5 ms. The HD is increased by 15% when the SB value is 10%, the SS is 10% and the SR is 80%. This is because the present slice delay is higher. Thus, the handover to another slice is needed.

We increase the value of SD to 0.9 ms in Fig. 9.23. Comparing the results with Fig. 9.21 and Fig. 9.22, we can see that the HD values have increased significantly. For SD 0.9 ms, SB 10%, all HD values are higher than 0.5. Thus, the mobile device will make a handover to another slice.

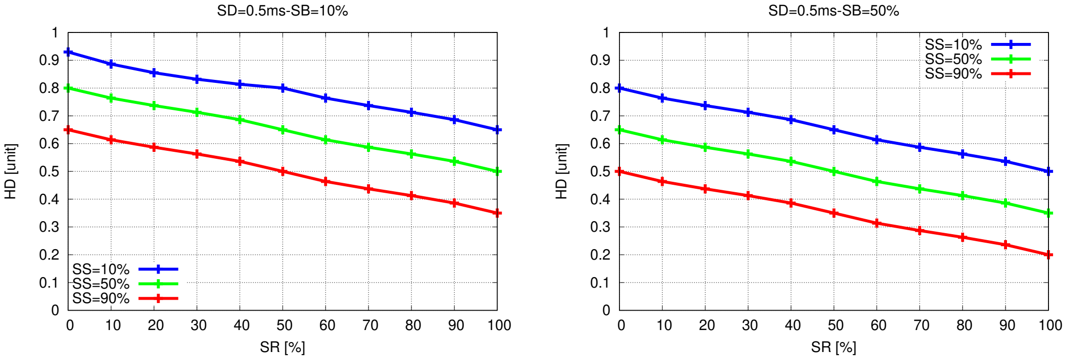


(a) SB=10% (b) SB=10%



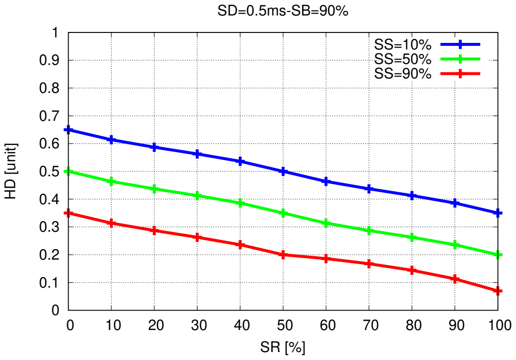
(c) SB=90%

FIGURE 9.21: Simulation results for FHM3 (SD=10%).



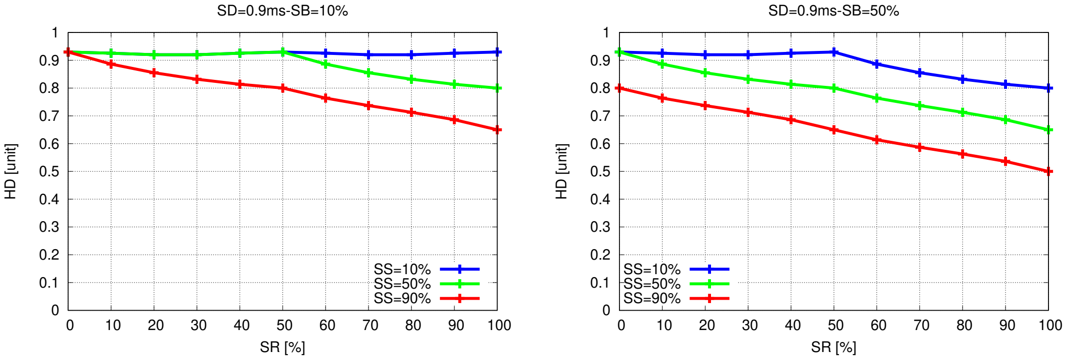
(a) SB=10%

(b) SB=50%



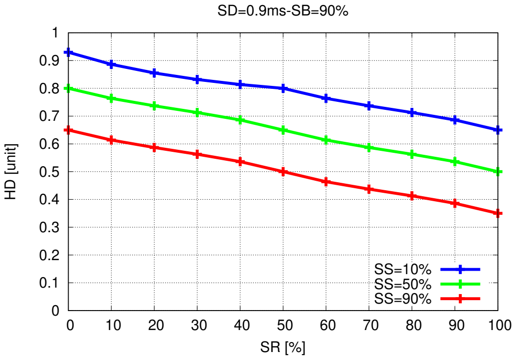
(c) SB=90%

FIGURE 9.22: Simulation results for FHM3 (SD=50%).



(a) SB=10%

(b) SB=50%

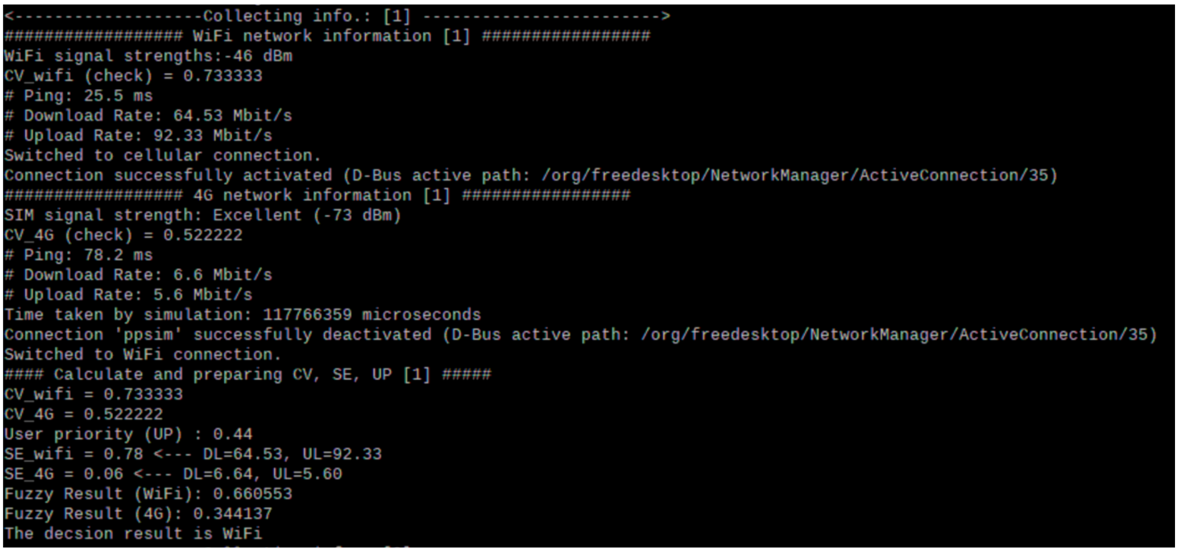


(c) SB=90%

FIGURE 9.23: Simulation results for FHM3 (SD=90%).

9.4 Result of FRSM Testbed

A snapshot of testbed operation is shown in Fig. 9.24. It shows a user initiating a data collection sequence for RAT selection, with the system first evaluating Wi-Fi, indicating a strong signal (-46 dBm) and good coverage (CV of 0.73), followed by a good download and upload speeds. Upon switching to a cellular connection, the 4G network data reveals good SIM signal strength (-73 dBm) but lower download and upload speeds compared to Wi-Fi. The system calculates CV, SE, and UP, with user priority set at 0.44. The output of the system for Wi-Fi (Fuzzy Result: 0.66) is better than 4G (Fuzzy Result: 0.34), leading to the final decision to connect to Wi-Fi network.



```
<-------------------Collecting info.: [1] ------------------------>
################## WiFi network information [1] #################
WiFi signal strengths:-46 dBm
CV_wifi (check) = 0.733333
# Ping: 25.5 ms
# Download Rate: 64.53 Mbit/s
# Upload Rate: 92.33 Mbit/s
Switched to cellular connection.
Connection successfully activated (D-Bus active path: /org/freedesktop/NetworkManager/ActiveConnection/35)
################## 4G network information [1] #################
SIM signal strength: Excellent (-73 dBm)
CV_4G (check) = 0.522222
# Ping: 78.2 ms
# Download Rate: 6.6 Mbit/s
# Upload Rate: 5.6 Mbit/s
Time taken by simulation: 117766359 microseconds
Connection 'ppsim' successfully deactivated (D-Bus active path: /org/freedesktop/NetworkManager/ActiveConnection/35)
Switched to WiFi connection.
#### Calculate and preparing CV, SE, UP [1] #####
CV_wifi = 0.733333
CV_4G = 0.522222
User priority (UP) : 0.44
SE_wifi = 0.78 <--- DL=64.53, UL=92.33
SE_4G = 0.06 <--- DL=6.64, UL=5.60
Fuzzy Result (WiFi): 0.660553
Fuzzy Result (4G): 0.344137
The decsion result is WiFi
```

FIGURE 9.24: A snapshot of testbed operation.

The testbed results for different CV values are shown in Fig. 9.25, Fig. 9.26 and Fig. 9.27. They show the relationship between RDV and SE for different levels of UP. The averaged lines in red, green and blue colors represent different UP levels (10%, 50%, 90%). Each dot represents a data point from a test case for each technology (WiFi, 4G and 5G).

In Fig. 9.25 the CV value is 10%. We see that by increasing SE and UP values, the RDV is increased. Specifically, when SE increases from 10% to 50%, there is a 16% increase in RDV, and a further 18% increase when SE increases from 50% to 90%. This trend suggests that for users with high priority, the RAT with greater transmission bandwidth (higher SE value) will have a higher RDV. When UP is decreased from 90% to 50%, and further from 50% to 10%, the RDV is decreased by 13% and 6%, respectively, when SE is 90%. This result indicates that when a user has a low priority, the RAT selection mechanism will allocate resources that might result in lower QoS, suggesting that higher priority users are favored in the allocation of higher QoS network resources.

When CV value is increased from 10% to 50% in Fig. 9.26, the RDV increases by 6% for users with a 90% UP and a SE value of 50%. This suggests that better coverage values contributes to a higher possibility of selecting a RAT, especially for high-priority users. By increasing CV to 90% in Fig. 9.27, we see that RDV is increased compared with results in Fig. 9.25 and Fig. 9.26.

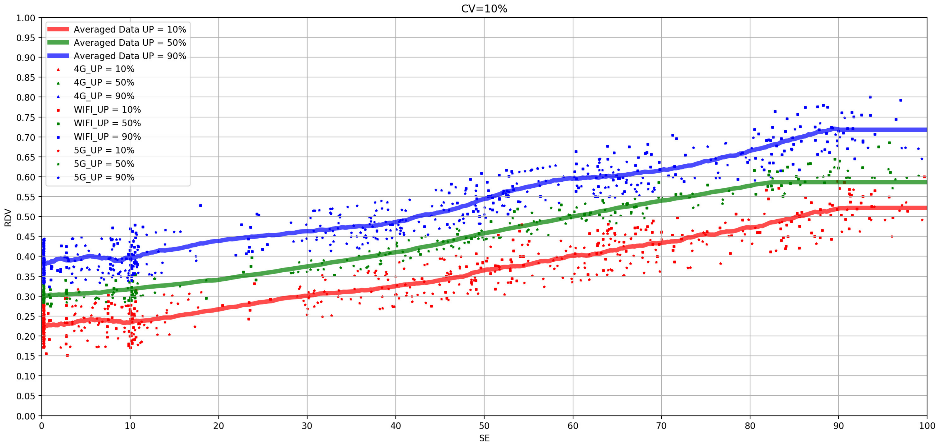


FIGURE 9.25: Testbed results for CV=10%.

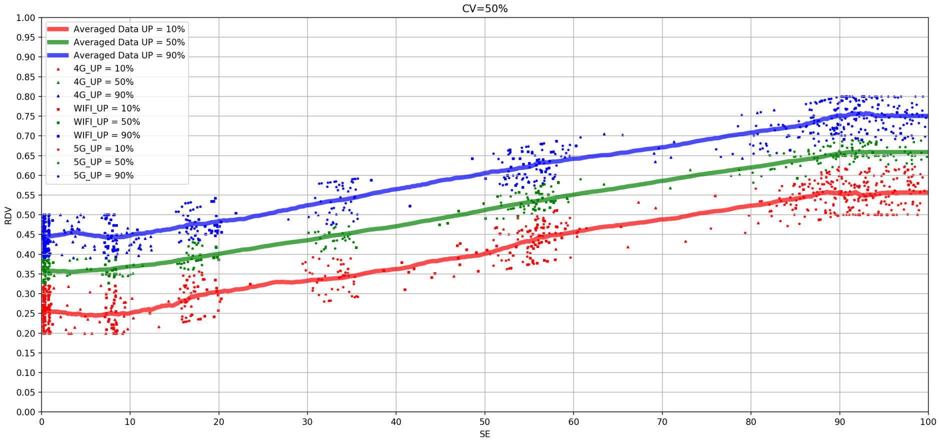


FIGURE 9.26: Testbed results for CV=50%.

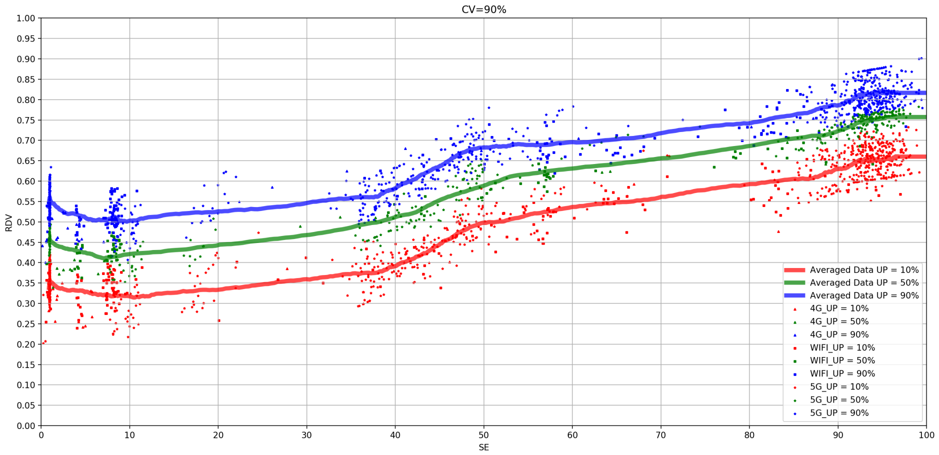


FIGURE 9.27: Testbed results for CV=90%.

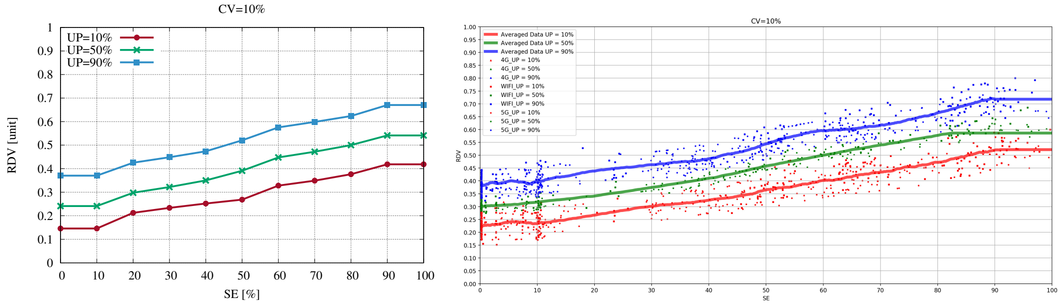
9.5 Comparison of FRSM Simulation and Testbed results

In Fig. 9.28, we show The comparison of FRSM Simulation and Testbed results. This comparison is made across three scenarios when the CV value is 10%, 50% and 90%.

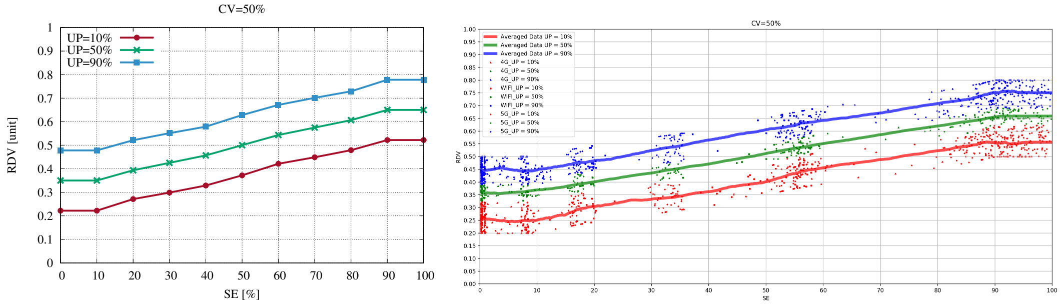
The simulation results (graphs on the left) suggest a structured and predictable relationship between the SE and RDV, showing smooth curves for three different prediction intervals. These are likely based on mathematical models and provide an idealized expectation of system performance.The testbed results (graphs on the right), with actual experimental data, show a higher degree of variability and noise, which is typical in real-world measurements due to numerous factors that can introduce unpredictability.

In simulation and experimental results for CV 10%, we can see a similar trend with a noticeable spread of data points. The actual measured RDV values at various points of SE, particularly at higher SE percentages, are slightly higher than the simulation results. For example, at SE=70% and UP=90%, the value of RDV for simulations is approximately 0.6, whereas the testbed results show data points extending beyond 0.65. Also, considering the impact of UP on RDV, we changed the UP value to 10%, 50% and 90%. In the testbed results (see Fig. 9.28(b)), when we changed the UP 10% to 50%. and 50% to 90% at SE 50%, the RDV value is increased by 10% and 10%, respectively. But, in the case of simulation results (see Fig. 9.28(a)), the RDV value is increased by 13% and 12%, respectively. So, the difference between simulations and experiments results is very small.

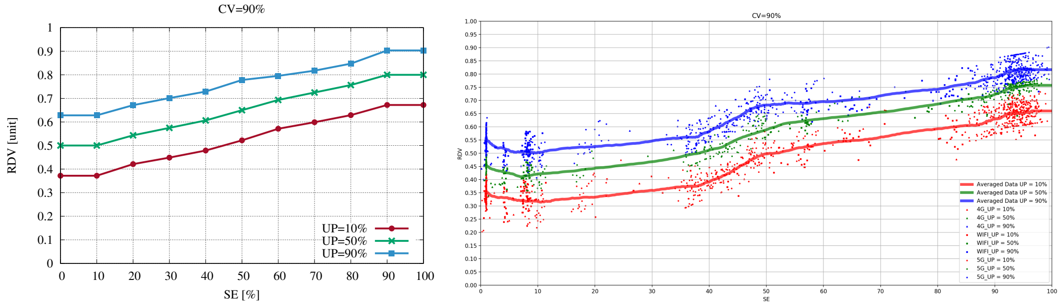
In case when CV is 50%, the testbed results (see Fig. 9.28(d)) are concentrated is some Se values. By comparing with the case when CV value is 10% (change from 10% to 50%), the RDV value increased by 6% for users with UP value of 90% and



(a) Simulation results for CV=10% (b) Testbed results for CV=10%



(c) Simulation results for CV=50% (d) Testbed results for CV=50%



(e) Simulation results for CV=50% (f) Testbed results for CV=90%

FIGURE 9.28: FRSM Simulation and Testbed results

SE value of 50%. For simulation results, the RDV value increased by 10%. In this scenario, the difference of simulation results with experimental is a little bit higher compared with the case when CV is 10%, but still is smal and the trend is the same.

In case when CV is 90%, the simulation results (see Fig. 9.28(e)) indicate that the RDV values are increased compared with the case of CV 10% and 50%. When UP is 90% and SE is 90%, the RDV value is 0.9. In the testbed results, we see a concentration of data when SE is between 80% and 100%. In the simulation results, we consider the range of SE values between 90% and 100%, and UP is 90%, the RDV value is 0.9. In the testbed results, the RDV (on the average trend line) is approximately 0.8, but we can see that the scattered data points are close to 0.9. This shows that the simulation results and experimental results are very close.

Chapter 10

Conclusions

10.1 Summary of Thesis

This thesis comprises ten chapters. Chapter 1 introduced the background, motivation, contribution and structure of this thesis.

Chapter 2 presented wireless networks. This chapter provides a comprehensive overview of wireless networks, categorizing them based on coverage area and topology, and detailing their evolution through the generations of mobile telecommunications from 1G to 5G. Each generation has marked significant advancements in technology, enabling higher data rates and connectivity that have been pivotal in developing smart city infrastructures. Also, it presents the role of wireless networks in smart city which uses wireless network as the fundamental connectivity infrastructure. However, the expansion of wireless networks also introduces complex security and privacy challenges. Protecting these networks against unauthorized access, data breaches, and other cyber threats is increasingly critical, necessitating robust security measures, continuous monitoring, and the implementation of advanced encryption technologies to safeguard data and user privacy in our interconnected world.

In Chapter 3, we presented specifically 5G wireless networks, providing a detailed description of the 5G network architecture and the transition from 4G to 5G, including the integration of 4G technologies within 5G frameworks. This transition inspired the development of 5G operational modes, namely NSA and SA. Additionally, the chapter explores architectural innovations integral to 5G, such as NFV, SDN, NS, and so on. These technological advancements are crucial for understanding the capabilities and versatility of 5G networks.

Then, Chapter 4 provided an in-depth exploration of Software-Defined Networking (SDN), focusing on its structure as well as its advantages and disadvantages specifically within the context of 5G wireless networks. This analysis includes a thorough examination of how SDN's architectural components contribute to the enhanced functionality and efficiency of 5G systems, while also addressing the potential challenges and limitations that SDN may introduce in these advanced networks.

In Chapter 5, we discussed key network management techniques, including call admission control, handover processes, and RATs. This chapter details how these components are critical for maintaining network efficiency and service quality in mobile communication systems, focusing particularly on their implementation and impact within complex network environments.

In Chapter 6, we introduced a range of intelligent algorithms that play a pivotal role in optimizing network operations. These include GA, NNs, and PSO. The chapter provides an overview of each algorithm's fundamental principles and discusses their practical applications in enhancing network performance and decision-making processes.

Chapter 7 introduces FL, we provided a detailed exploration of the foundational theories behind fuzzy logic, fuzzy sets, and fuzzy systems. These concepts are examined in the context of the fuzzy logic applications discussed in this thesis, ensuring a comprehensive grasp of the methodologies involved. The provided concepts are discussed in regards to the application of fuzzy logic presented in this thesis in order to enable a complete understanding of the proposed systems, which are detailed in Chapter 8.

In Chapter 8, we presented in details of all fuzzy-based models, offering detailed descriptions of input and output parameters. The set of linguistic values for each parameter, the selected membership functions, and the FRB for every fuzzy logic controller within the proposed systems were detailed, providing essential information for replicating the simulation results. After explaining each model, we introduced the testbed that we implemented to carry out experiments and to evaluate the system experimentally.

Chapter 9 explained evaluation simulation results for various input parameters and experimental results. The comparison between simulation and experimental results is also discussed.

The last chapter, Chapter 10, concludes the thesis, summarizing the main research findings and future research directions.

10.2 Concluding Remarks

In this thesis, we proposed and implemented a Fuzzy-based system for resource and traffic management in 5G Wireless Network. Our system comprises three modules: the FRSM, responsible for determining the selection of RAT in 5G wireless networks to connect users appropriately; the FACM, which decides whether to accept or reject a connection request from a new user based on network traffic conditions; and the FHM, which oversees inter-slice and inter-eBS handovers to enhance QoS during handovers in 5G wireless networks. We have incorporated various input parameters into these modules. To assess the proposed system, we have introduced different models and compared simulation results with experiment results. From the simulation results and experiment results, we conclude as follows.

10.2.1 Conclusions for FRSM

We presented the FRSM, determining the most suitable RATs for connecting users effectively based on various different network slicing parameters. This mechanism ensures optimal user connectivity and network efficiency. We considered three models: FRSM1, FRSM2 and FRSM3.

In FRSM1, increasing CV, UP, and SE in FRSM1 leads to a higher RDV. This means that decisions regarding RATs become more important. Improved coverage means the network reaches more areas, increasing the need for efficient RAT decisions to handle more users. Higher user priority highlights the importance of serving specific user types quickly, requiring precise RAT decisions to meet different service needs. Additionally, better spectral efficiency maximizes resource use, making RAT decisions critical for maintaining service quality and network efficiency. For example, RDV values are more than 0.5 (See Fig. 9.1 (c)), it indicates that the user will select a better RAT with wider coverage and better bandwidth for medium and high user priority (UE 50% and 90%).

In FRSM2, we introduced a new input parameter, RL, to calculate RDV. Our simulation results have shown that when CV, UP and SE increase, RDV also increases. However, when RL increases, RDV decreases, indicating higher network congestion or heavier load, prompting a decrease in RDV as RAT decisions become more challenging due to increased resource contention and potential service degradation. Therefore, while enhancing in coverage, user priority, and spectral efficiency enhance RDV, an increase in RAT load exerts a contrary effect, emphasizing the intricate balance required in managing network resources for optimal performance.

For FRSM3, we considered QoE a new input parameter for calculating RDV. The simulation results show that when the CV, UP, SE, and QoE parameters are increased, the RDV value increases. Introducing QoE as a factor further emphasizes the significance of user satisfaction and service quality for making RAT decisions. Therefore, the simultaneous increase in CV, UP, SE, and QoE parameters signifies a comprehensive enhancement of network performance, reflecting a higher RDV as RAT decisions become increasingly critical in maintaining superior service quality and user satisfaction levels.

QoE is crucial for RAT selection, intertwining with various network factors. A balanced blend of high capacity, user throughput, and reliable connectivity ensures superior digital experiences. For this reason, we proposed two schemes: FSQoE1 and

FSQoE2. The FSQoE1 considers three parameters: NC, EEUT and Cn. The FSQoE2 considers Se as the fourth parameter. The highest QoE value is attained when the RAT provides a big NS, EEUT, high Cn, and very strong Se. This emphasizes the importance of a balanced combination of network performance and security measures in achieving optimal QoE in 5G networks. Despite its increased complexity, FSQoE2 outperforms FSQoE1 in evaluating QoE because it provides a more comprehensive assessment incorporating network security considerations. By integrating the Se parameter, FSQoE2 offers a more holistic view of QoE, acknowledging the importance of security alongside other parameters.

Comparing FRSM1, FRSM2 and FRSM3 have shown that FRSM2 and FRSM3 are more complex because they consider of additional parameters such as RL in FRSM2 and QoE in FRSM3. Despite their increased complexity, FRSM2 and FRSM3 offer better performance in evaluating RDV. This is because they provide a more comprehensive assessment by incorporating factors beyond just CV, UP, and SE, which are considered in FRSM1. By including RL and QoE parameters, FRSM2 and FRSM3 offer a more holistic view of network performance and user satisfaction, thus enabling more accurate and effective evaluation of RDV. Therefore, while FRSM2 and FRSM3 may be more complex, their enhanced performance in assessing RDV underscores their greater utility in evaluating and optimizing RAT decisions.

10.2.2 Conclusions for FACM

The FACM determines whether to accept or reject connection requests from new users based on four input parameters: QoS, SP, URDT and SOC. Simulation results indicate that as SOC increases, the AD value decreases, indicating a lower likelihood of acceptance due to potential network overloading. Conversely, higher values of QoS, SP, and URDT lead to an increase in the AD value, signaling a greater possibility of acceptance as these parameters signify better service quality, higher slice priority, and quicker response times for user requests, respectively. This nuanced decision-making process ensures efficient resource allocation and maintains satisfactory service levels amidst varying network conditions.

10.2.3 Conclusions for FHM

The FHM considers inter-slice and inter-eBS handovers to enhance QoS during handovers in 5G wireless networks. We presented for FHM different NS parameters. We considered two models: FHDM1 and FHDM2. We evaluated the proposed models by simulations. From the simulations results, we conclude as follows. The FHDM2 is more complex than FHDM1, but it has better HD since it has four parameters.

For both FHDM1 and FHDM2 models, we see HD value increases with higher values of SD and SL. This suggests that as slice delay and loss increase, the handover decision quality improves, likely because higher delay and loss indicate poorer performance, prompting the system to initiate handovers for better service. Conversely, the HD value decreases as SB and SR values increase. This implies that as slice bandwidth and reliability improve, the need for handovers decreases, leading to a lower HD value. This trend highlights the importance of considering various network parameters in handover decision-making to ensure optimal QoS in 5G wireless networks. For better QoS, a mobile device (user) connected to the present slice, which has a high latency, low bandwidth, heavy load, and a low of reliability should to make handover to another slice. For example, in the results of FHDM2, the HD value is more than 86% when SD is 90%, SB is 10%, SR is 10% and SL is 90%.

10.2.4 Conclusions for FRSM Testbed

We presented the implementation of a simulation system and a testbed using FL for selection of RATs in 5G wireless networks. We considered three input parameters: CV, UP and SE, while the output parameter is RDV.

The simulation system effectively shows the intricate relationships between CV, UP, SE, and RDV, thereby enhancing our understanding of how these factors influence RAT decision-making processes. By leveraging these insights, network operators can make informed adjustments to optimize coverage, prioritize users effectively, and enhance spectral efficiency, ultimately improving RAT decisions and enhancing overall network performance.

To determine the accuracy of the system, we compared the simulation results with experimental results.

The results show the same trend. The actual measured RDV values at various points of SE, particularly at higher SE percentages, are slightly higher than the simulation results. For instance, at CV 10%, SE 70% and UP 90%, the simulated RDV value is approximately 0.6, while the testbed results demonstrate data points extending beyond 0.65. This comparison revealed that the simulation and experimental results trend is the same. Also, the simulation and experimental data are very close.

10.3 Future Directions

In our future research, to fully harness the system's capabilities, it's crucial to assess its accuracy. This evaluation reveals which parameters contribute most to false positive results and highlights areas for enhancement to minimize false negatives. Below, we outline future enhancements planned for the proposed system.

In our testbed for FRSM, we plan to implement SIM8202G-M2 5G HAT (5G/4G/3G Support, Snapdragon X55, Multi Mode Multi Band) to SDN controller Raspberry Pi and build the testbed prototype 2 (See Fig. 10.1) which will collect 5G information and make RAT selecting decision to UE. Also, we conduct additional experiments using the testbed by considering more input parameters.

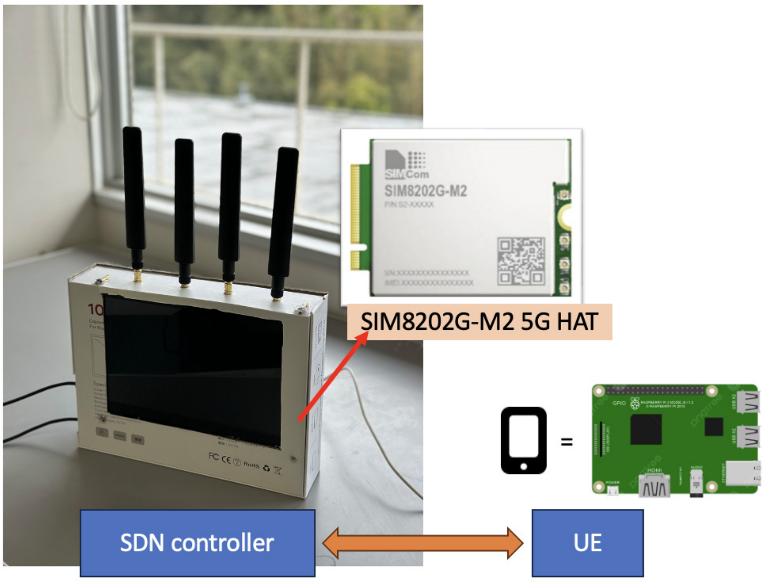


FIGURE 10.1: Testbed prototype 2.

We would like to implement testbeds for FASM and FHM and compare simulation results and experimental results. By analyzing both simulation results and experimental data, we aim to understand how each model performs in different situations. This approach will help us draw clear conclusions about the effectiveness of each model.

Recently, many researchers are discussing 6G wireless networks, envisioning even faster speeds, lower latency, and transformative capabilities. So, we plan to extend our research work for 6G wireless networks.

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