Developing an SDWN Architecture for Wireless Network Engineering to Support a Quality of Experience Aware Handover

By

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DECLARATION

I, Omar Aldhaibnai, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm this has been indicated in the thesis.

Omar Aldhaibani

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ABSTRACT

The massive growth of data consumption and the variety of wireless technology emergence has made the handover (HO) an attractive research topic nowadays, mainly due to the popularity of Wireless Local Area Networks (WLANs), which allow users to reach high-speed data communication while they are in movement. Moreover, mobile devices such as tablets and smartphones have also become increasingly popular due to their low cost and ease of use, and an increase in mobile device use is expected to accelerate in the coming years, along with the availability and use of applications such as real-time services and online gaming. The traditional HO methods will likely not meet the requirements of mobile devices for modern applications due to the lack of intelligence, lack of awareness Quality of Service (QoS) and Quality of Experience (QoE) requirements of mobile users.

We, therefore, introduce a novel architecture that supports horizontal HO in homogenous networks. This architecture is based on the Software-Defined Wireless Networking (SDWN) concept, where the wireless network is controlled centrally and the wireless Access Points (APs) are programmable. In this architecture, HO algorithms will assist wireless users to find the network that could best support the application requirements through Quality of Service (QoS) and Quality of Experience (QoE) management policies.

The first HO algorithm proposed in this thesis is called Quality of Experience Oriented Handover Algorithm. This algorithm will guarantee the best possible connectivity to the users in terms of their QoE and QoS requirements and outperforms the traditional methods in a sparse network environment. The second contribution is called Optimised Handover Algorithm for Dense WLAN Environments. This algorithm has been designed to address dense network environments via taking into consideration the Adaptive Hysteresis Value (AHV). The AHV

will help the Optimised Handover Algorithm via reducing the so-called ping-pong effect. This contribution shows promising performance results by selecting the best candidate AP, decreasing the number of redundant HO and avoiding the ping-pong effect.

The final contribution is called Priority Based Handover Algorithm. We extended our proposed SDWN architecture in order to include the concept of prioritising users and make a smart decision during the process of HO. This algorithm will prioritise a certain class of users to avoid the effect of the over-congestion. The results show that the approach based on priority outperforms the state of the art and provides better QoE to the high priority users despite the over-congestion situation.

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THESIS ACRONYMS

3GPP	3rd Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
AP	Access Point
AHV	Adaptive Hysteresis Value
API	Application Programming Interfaces
BE	Best effort
BS	Base Station
BW	Bandwidth
BSSID	Basic Service Set Identifier
FLCT	The Fuzzy Logic Control Theory
FHOD	Fuzzy Handover Decision
GSM	Global System for Mobile communications
HO	Handover
LTE	Long Term Evolution
LVAP	Light Virtual Access Point
MAC	Medium Access Control
MAG	Mobility Access Gateway

MCDM	Multi Criteria Decision Making
MN	Mobile Node
MIMO	Multiple Input Multiple Output antenna
NFV	Network Function Virtualisation
NFVI	NFV Infrastructure
VoIP	Voice over IP
OFDMA	Orthogonal Frequency Division Multiple Access
ONF	Open Networking Foundation
PHY	Physical Layer
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RSS	Received Signal Strength
SDN	Software-Defined Network
SDWN	Software-Defined Wireless Network
SINR	Signal to Interference & Noise Ratio
STA	Station
SSID	Service Set Identifier
TCP	Transmission Control Protocol

UMTS	Universal Mobile Telecommunications System
VNF	Virtual Network Functions
VNO	Virtual Network Operator
VXLAN	Virtual Extensible LAN
WF	Weighted Fair
WLANs	Wireless local area networks

LIST OF PUBLICATIONS

Conferences and Workshops

- Omar Aldhaibni, Faycal Bouhafs, Michael Mackay and Alessandro Raschellà "An SDN-based Architecture for Smart Handover to Improve QoE in IEEE 802.11 WLANs" The 32-nd IEEE International Conference on Advanced Information Networking and Applications (AINA) 2018.
- Omar Aldhaibni, Mustafa Hamid AL-Jumail, Faycal Bouhafs, Michael Mackay and Alessandro Raschellà, Ghulam Mohi-Ud-Din, Ali Alfoudi "An SDWN based Architecture for Enormously Dense Wireless Networks to Optimise the Handover Performance in WLAN" the 5th Springer International Conference on Interactive Digital Media (ICIMD) 2018.
- Amhmed Bhih, Michael Mackay, Omar Aldhaibani, Mohammed Al-khafajiy, Faycal Bouhafs "Modelling and Analysis of Performance Characteristics in a 60Ghz 802.11ad Wireless Mesh Backhaul Network for a urban 5G Deployment" 22nd ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM'19).

Chapter 1 Introduction

1.1 Introduction

Wireless local area networks (WLANs) have become virtually ubiquitous [1]. As the recent availability of hands-free technology increases, this allows users to interact with rich multimedia services in a hassle-free manner [2]. Mobile devices, such as tablets and smartphones have also become increasingly popular due to their low cost and ease of use [3]. Researchers must be prepared for further developments in the coming years due to the advancement of applications, such as real-time services and online gaming which consume big data, and that could be an issue in a dense environment. This will cause significant growth in data traffic as a result. Figure 1-1 demonstrates the acceleration of smartphone uptake that is forecast to the year 2022 when they are expected to overwhelm other devices by 70.1% [4][5].

IEEE 802.11 is the standard that includes a set of the physical layer (PHY) and media access control (MAC) layer specifications for implementing WLAN [6]. In addition to WLAN, there are various other wireless technologies such as Universal Mobile Telecommunications System (UMTS), and Long-Term Evolution (LTE) that allow Internet connections over mobile networks. These numerous technologies have resulted in a heterogeneous wireless environment, where devices have the ability to connect to many different wireless networking providers using traditional network infrastructures [7]. However, these traditional infrastructures are not designed to meet the requirements of seamless mobility and large volumes of traffic [8], [9]. Moreover, these infrastructures do not always guarantee the service to the end-users [10].

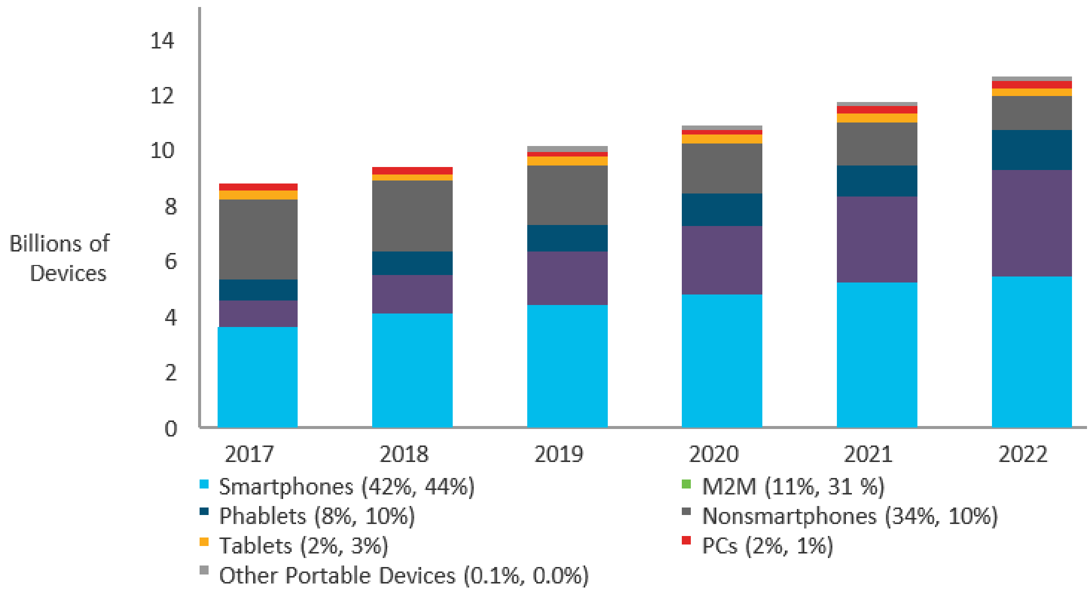

Figure 1-1: The global growth of mobile smartphones [11]

To overcome these problems, various methods have been used to evaluate and enhance Quality of Service (QoS) which refers to the performance of a network and Quality of Experience (QoE) which refers to a measure of the overall experienced service at the end-users. In fact, since the invention of mobile networks, the protocols have constantly evolved to ensure the best possible service to customers in terms of data rates and communication experience. The evolution of mobile networks has now passed the fourth generation (4G), which provides enhanced data rates via LTE, and has now reached the fifth-generation (5G). 4G networks have more support for heterogeneous networking technologies to achieve the best service for their users in terms of QoS and flexibility when using multi-services, such as navigation services and seamless connection [10]. Correspondingly, the IEEE 802.11 standard has also significantly improved, from the first generations (a/b) [12] when the speed was up to 2 Mbps, until reaching speeds up to 1.3 Gbps in the fifth version (i.e., IEEE 802.11ac) [8], and 4.8 Gbps in IEEE 802.11ax, which is the most recent standard [13] [10]. This has the effect of improving the overall user experience, supporting, for instance, 4K video streaming in hotspots, channel bonding and connections that allow handling more clients [8]. Additionally, in 2008, IEEE 802.11r has been proposed to include all the IEEE 802.11 standards that enhance the HO process. Specifically, IEEE 802.11r has significantly reduced the length of time that connectivity is interrupted between AP and STA through the HO process. It reduced the roaming time from 525 ms into 42 ms compared to IEEE 802.1x. Additionally, this results in reducing the packet loss from 1.8% into 0.2% and can significantly improve the real-time interactive services such as online gaming, video and VoIP [14].

However, in 802.11 networks, the clients are not managed and still need to manually apply the handover (HO) process in order to switch between different Access Points (APs) or different providers while they are in movement [15], [16]. This limited capacity in traditional HO processes and the rapid evolution of applications could result in poor QoS and QoE. As such, a large number of works have been proposed to refine the HO process. The works using mobile terminals to make a decision, however, are limited in their capacity to detect the best available bandwidth (BW), since they do not consider QoS criteria and the load balancing at the APs [17]. Although a number of works have been reported in the literature to control HO management, it is still challenging to drive a powerful decision-based analysis approach [18].

In this context, the goal of this PhD project is to overcome the load balancing issue by designing and developing HO strategies through various decision-making methods that take into consideration the QoS and QoE requirements of the wireless users. The proposed methods are based on Fuzzy Logic Control Theory (FLCT) and implemented in a centralised controller relying on a Software-Defined Network (SDN) architecture. An SDN controller will be capable of monitoring and handling a set of APs to select the best candidate for each user through its global view of all the network.

1.2 Research Objectives and Novel Contributions

Our literature review shows that the existing HO solutions exhibit a number of limitations that affect the performance of mobile devices and ignore their requirements [22], [23]. These issues are caused by a lack of awareness within the wireless network of the performance requirements of the user's devices, the distributed nature of most handover solutions, and their complexity and poor scalability.

1.2.1 Objectives

The aim of this research project is to improve Wi-Fi user station (STA) experience by minimising the transition delay and assist the STA in choosing the best network that satisfies the application's QoS and QoE requirements. This research will focus on densely overlapping areas, where STAs have access to different APs, which can belong to different networks. Therefore, the objective is to design a novel architecture that supports seamless HO considering the STA's QoS and QoE requirements. Our design approach will be based on the latest developments in network architecture design and management, and more specifically Software Defined Wireless Network (SDWN) [19], that extends the SDN paradigm as will be explained in Chapter 3. Hence, in summary, the main objective of our research is to address the limitations of current HO techniques related to transition delays, complexity, and QoS/QoE awareness. We believe that these limitations can be addressed by achieving the following scientific objectives:

- To understand, analyse and identify major issues for the existing HO decision schemes, focused on QoS and QoE requirements in overlapping areas. We presented a detailed analysis of different research works regarding HO, resource allocation and mobility management in wireless networks. Specifically, we discussed in detail the existing techniques and solutions in this area together with their limitations.

- To design a centralised network architecture based on SDWN where wireless APs act as programmable wireless switches connected to a single controller or multiple controllers. We achieved this objective introducing a centralised intelligence into the network able to assist the HO process and address QoS and QoE. This centralised intelligence is implemented in a controller is based on SDWN. This controller is able to program data plane switches and implement different networking policies using an application programming interface.
- To design seamless HO based first on an *FLCT algorithm* that supports QoS and QoE for real-time applications. We achieved this objective implementing an algorithm at the application layer that ensures the best AP connection based on QoS/QoE requirements.
- To improve our initial approach based on *FLCT* in order to make it effective in large network environments with a high density of APs and STAs. This enhanced version will be called the *Optimised Handover Algorithm*. We achieved this objective introducing a new element in our HO approach in order to reach the optimal HO decision through the Adoptive Hysteresis Values (AHV) at the edge of QoE levels, which aid to avoid unnecessary ping-pong handovers.
- To further extend our work with the inclusion of STA prioritisation. This version is based on prioritisation that relies on the MCDM concept and will be called the *High and Low Priority-based* algorithm. We achieved this objective implementing a priority-based handover algorithm in the application layer. The algorithm optimises the QoE for

the users according to their priorities. This algorithm will always provide the best QoE to the high priority users at the expense of low priority users.

1.2.2 Novel Contributions

As we explained above, existing HO methods do not meet the requirements of mobile devices and cause long latency due to the lack of intelligence which is the optimised decisions and the capable of high-level data routing. In this context, this project will contribute to enhancing HO processes in the case of Wi-Fi networks. In summary, the proposed approach will provide the following novel contributions:

- Design a novel architecture, based on the SDWN paradigm, which will implement the proposed HO algorithms in homogeneous networks. This novel architecture will allow the centralised controller to provide real-time monitoring to collect data from the managed APs and STAs, which will support the HO process.
- Define novel wireless network management algorithms by applying the Fuzzy Logic Control Theory (FLCT). The novel FLCT wireless network management will receive real-time measurements as a set of parameters from the controller called membership values, which represent the QoE requirements.
- Develop a strategy that will support the designed HO algorithms in large network environments with a high density of APs and STAs. This novel strategy will enhance the performance results by reducing the redundant HO, and the corresponding messaging overhead through the use of Adaptive Hysteresis Values (AHV).
- Develop an approach to prioritise users in order to facilitate HO process for the purpose of improving QoE. This novel approach will utilise the concept of users' prioritisation to make a smart decision during the process of HO classifying the user into two

categories (i.e., high user and low priority user). This approach will guarantee the best QoE for the high priority users.

Therefore, this PhD project addresses the limitations found in the state of the art as follows:

I. It will address the HO problem by taking into consideration the user's expectations in terms of QoS and QoE.

II. It will offer an innovative SDWN-based architecture, through which a centralised controller is able to monitor all the nodes even in large networks by gathering the radio environment information that will allow it to efficiently address the above-mentioned QoS and QoE.

1.3 Structure of the Thesis

The thesis is structured as follows: Chapter 2 presents the literature review in terms of HO strategies. Then, Chapter 3 illustrates the SDN, SDWN and the proposed design architecture, while Chapter 4 presents the proposed first version of the QoE Oriented HO algorithm, i.e., FLCT algorithm. Chapter 5 presents the Optimised Handover Algorithm for Dense WLAN Environments. Chapter 6 illustrates Priorities Based Handover Algorithm, i.e., High and Low Priority-based algorithm. Finally, Chapter 7 provides conclusions and future works.

Chapter 2 Background Research and Related Work on Handover

2.1 Introduction

A Handover (HO) is the process of moving a Mobile Node (MN) or also called STA from one wireless network to another, or moving an STA from one wireless provider to another [20]. Generally, the HO is divided into three phases: Handover Information Gathering, Handover Decision and Handover Execution [20]. The Handover Information Gathering phase, also known as a system discovery phase, focuses on collecting information in order to identify the need for an HO and subsequently initiating it when it is necessary.

The Handover Decision phase focuses on providing user satisfaction by trying to determine the most appropriate access network when making an HO decision. This is a challenging task, and there are many approaches that have been proposed in the literature. These approaches can be divided into two categories: static and dynamic. Static approaches focus on the user profile [10], whereas dynamic approaches focus on mobility and Received Signal Strength (RSS) [20].

The Handover Execution phase confirms the change of channel and network in a seamless way based on the outcome of the decision phase, and preferably before the previous connection is terminated [21]. In this chapter, we investigate the state of the art on HO techniques.

2.2 WLANs in Enterprise Environments

2.2.1 Introduction of IEEE 802.11

IEEE 802.11, also known as Wi-Fi, includes a set of functionalities and specifications for the implementation of wireless local area networks (WLANs). The number 802 refers to the date of the first meeting of the association, which was on the 11^{th} of February 1980 according to [22]. The first specification of the Wi-Fi standard was released in 1997 under the name of 802.11, which included the set of the physical layer (PHY) and media access control (MAC) specifications for implementing WLAN [6] with data rates up to 2 Mb/s using the 2.4 GHz band. The IEEE 802.11 standard has meaningfully improved, from the first generations using the 2.4GHz band to the most recent ones using the 5GHz band.

Table 2-1: The most important versions of IEEE 802.11.

IEEE 802.11 Standard Version	Year of Release	Data Rate	Approximately Transmission Range	Frequency Band
IEEE 802.11	1997	Up to 2Mbps	Indoor up to 20 feet	2.4GHz
IEEE 802.11b	1999	Up to 11Mbps	Indoor up to 150 feet	2.4GHz
IEEE 802.11a	1999	Up to 54Mbps	Indoor up to 75 feet	5GHz
IEEE 802.11g	2003	Up to 54Mbps	Indoor up to 150 feet	2.4GHz
IEEE 802.11n	2009	Up to 600Mbps	Indoor up to 175 feet	2.4GHz/5GHz
IEEE 802.11ac	2013	Up to 1.3 Gbps	Indoor up to 270 feet	5GHz
IEEE 802.11ax	2019	3.5 to 14 Gbps	Indoor up to 270 feet	2.4GHz/5GHz

Table 2-1 shows the most important versions of the IEEE 802.11 standards and their data rate and transmission range.

IEEE 802.11ac is considered the most recent version, promising a high speed by increasing the throughput in band (5 GHz). This high speed has been reached by using the new technology Multiple Input Multiple Output antenna (MIMO). The main idea behind MIMO technology, which is illustrated in Figure 2-1, is to combine multiple signals for transmission over a single line or medium in order to increase the WLAN data rate and range [23]. In another words, at the same time, the data will travel through different antennas using the same channel. In that case, the receiver must have multiple antennas in order to receive all the sent data. The MIMO technology exploits the phenomenon of multipath propagation in which the signal travels towards the receiver in two or more paths. The functionality of MIMO is divided into three categories as precoding, spatial multiplexing and diversity coding. The transmitter performs precoding by using spatial processing. In order to enhance the received signal gain, single-stream beamforming is performed. However, the traditional method of beamforming does not work well in cellular networks. Therefore, precoding is applied to transform a single stream beamforming into multi-stream beamforming. In spatial multiplexing, the MIMO antenna is configured to split high-rate signal into many lower-rate signal streams. These lower-rate streams are transmitted in the same channel by the antenna. The spatial multiplexing technique is used to increase channel capacity in the presence of a high signal-to-noise ratio (SNR). The diversity coding technique is used in the absence of channel properties of the communication link. In this technique, the signal is coded using space-time coding and transmitted in a single stream.

Finally, the upcoming IEEE standard is 802.11ax, also known as Wi-Fi 6. It is similar to 802.11ac in terms of using the MIMO concept, but the 802.11ax will be more than 4x faster than 802.11ac and use multiple channels which significantly increase throughput. In detail, 802.11ax uses 160 MHz channels, the speed of streaming is 3.5Gbps for a single channel. With using MIMO, the total capacity could reach up to 14Gbps.

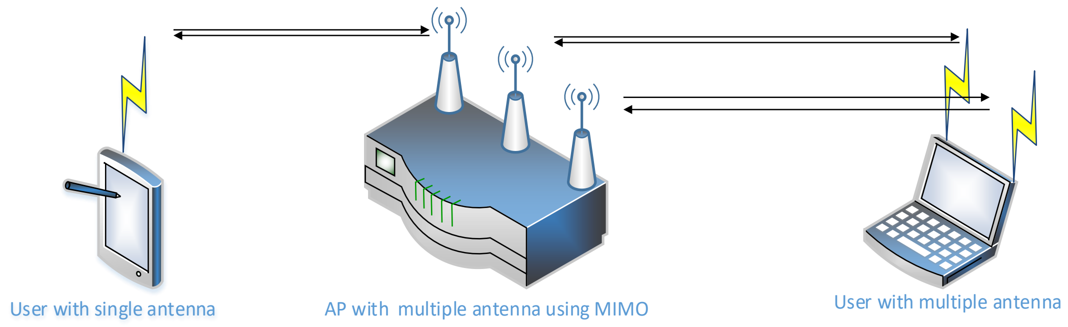

Figure 2-1: AP with multiple antenna MIMO

2.2.2 Deployment of WLANs in the Large-Scale network.

Due to the massive increase in the use of a smartphones and tablets, large-scale Wi-Fi deployment is considered an important challenge. Using Wi-Fi in large-scale networks in places such as airports, university campuses, stadiums and train stations will result in a massively dense network because of the number of the APs that have been used, or the number of users. This dense network will cause interference between APs in overlapping areas, which will reduce the quality of the received services. Typically, in large-scale Wi-Fi environments, the HO is considered an important process to enable a smooth transition of mobile users across different APs in order to support real-time applications (VoIP, video and online gaming).

2.3 Handover Process in WLANs

The HO process in WLANs is shown in figure 2-2. The shadow areas represent the coverage of the APs. In the beginning, the user is connected to AP1 and receives the best QoS. When the user is in the overlap area of both APs and starts moving away from AP1 towards AP2, the signal strength of AP1 starts decreasing and it affects the QoS for the user. In this case, when the signal from AP1 drops below a threshold, the user starts receiving stronger signals from AP2 as he is in the coverage area of AP2. In this situation, the handover process takes place.

In detail, the HO process is initiated by listing the available candidate APs. In WLANs the decision of HO is typically made by the STAs while in cellular networks the HO decision is made by mutual collaboration. Traditional techniques waited until the current AP signals are completely lost before HO. However, this approach did not provide an optimal solution due to service disruption. The currently deployed industry standards tackle this problem by maintaining a list of available APs in the background. The next step in the HO process is the assessment of the ability of the new AP to handle the traffic of the STA. If the new AP is running at its full capacity, then the HO process will not commence. When the AP has capacity for accepting a new STA, authentication is carried out between the STA and new AP. If the HO is between two different subnets, the STA is assigned a new IP address. However, taking a new IP address via DHCP demands extra delays during HO. Therefore, it is a best practice to avoid obtaining a new IP address if possible. At this point, the handover process is essentially complete.

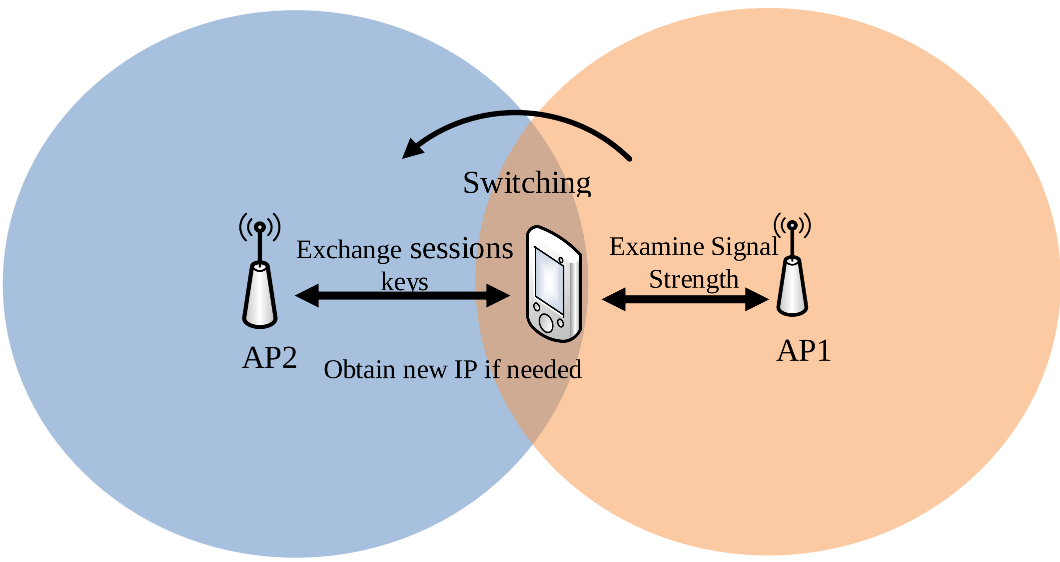

Figure 2-2: Handover process

2.3.1 Handover Techniques

HO Techniques can be classified into three types: Hard Handover, Soft Handover and Smart Handover. A hard handover is termed as break-before-make; the connection with the source (base station or AP) is first broken before making a new connection with the new candidate network [24]. This will obviously result in packet loss and latency and so is not ideal for streaming applications but is often the case for devices with a single interface.

A soft handover, which is also called Make-before-break, will allow the STA to establish a new connection with another candidate network before the loss of connection with the current source. In this type of connection, the user will receive better service as the connection can continue without interruption [25]. Figure 2-3 illustrates an example of soft and hard HO techniques in the case of WLANs.

Finally, a smart handover is an improved version of the soft handover, which provides a seamless handover without interruption of service. Specifically, a smart handover aims to choose the best possible service through all the available networks and even through the same WLAN provider by connecting to the best AP [26].

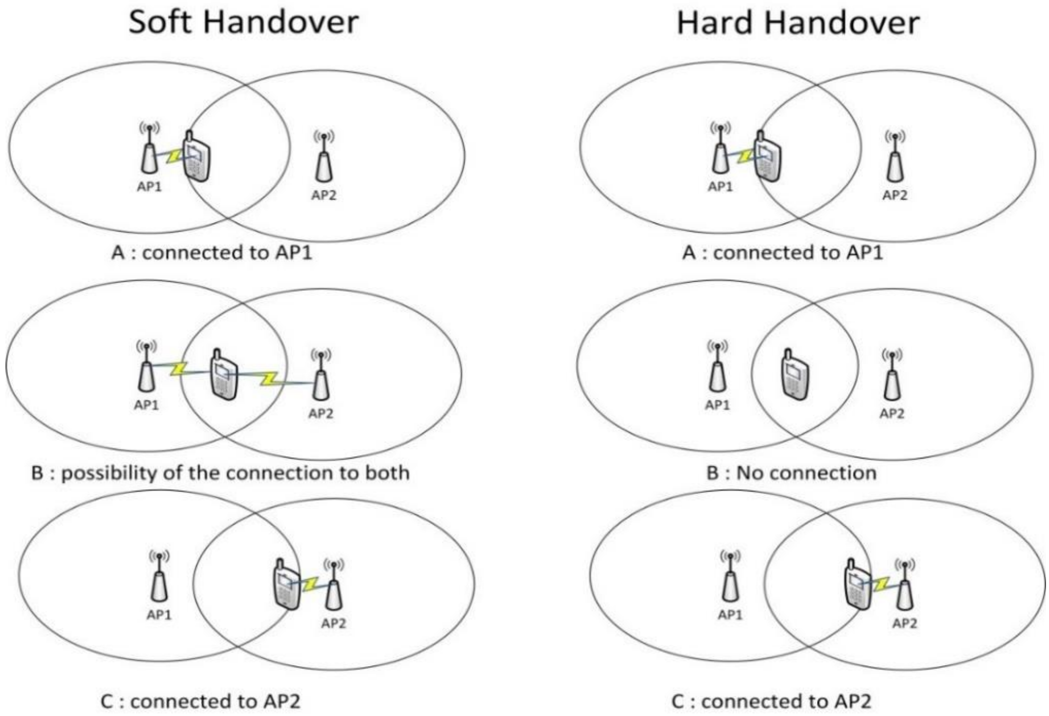

Figure 2-3: The difference between the soft and hard handover

2.3.2 Mobility Handover

A HO is an action of moving an STA from one AP to another or to a different wireless technology [3]. A HO can also be divided into the following three different types: Horizontal handover (HHO), Vertical handover (VHO) and Diagonal handover (DHO). An HHO occurs in different cells in the same network, also known as a homogenous network, whereas a VHO takes place between cells of different network technologies. Diagonal handover is the combination of horizontal and vertical handovers [4]. Specifically, a DHO occurs when the STA crosses different wireless cells that use a common underlying technology such as Ethernet, allowing the users to carry on running its applications with the required QoS from Wi-XX to Wi-YY networks [4]-[27]. Figure 2-4 shows the difference between HHO, VHO and DHO. In the figure, the Y-axis presents the different technologies (heterogeneous) and X-axis presents connections from the same technology (homogenous).

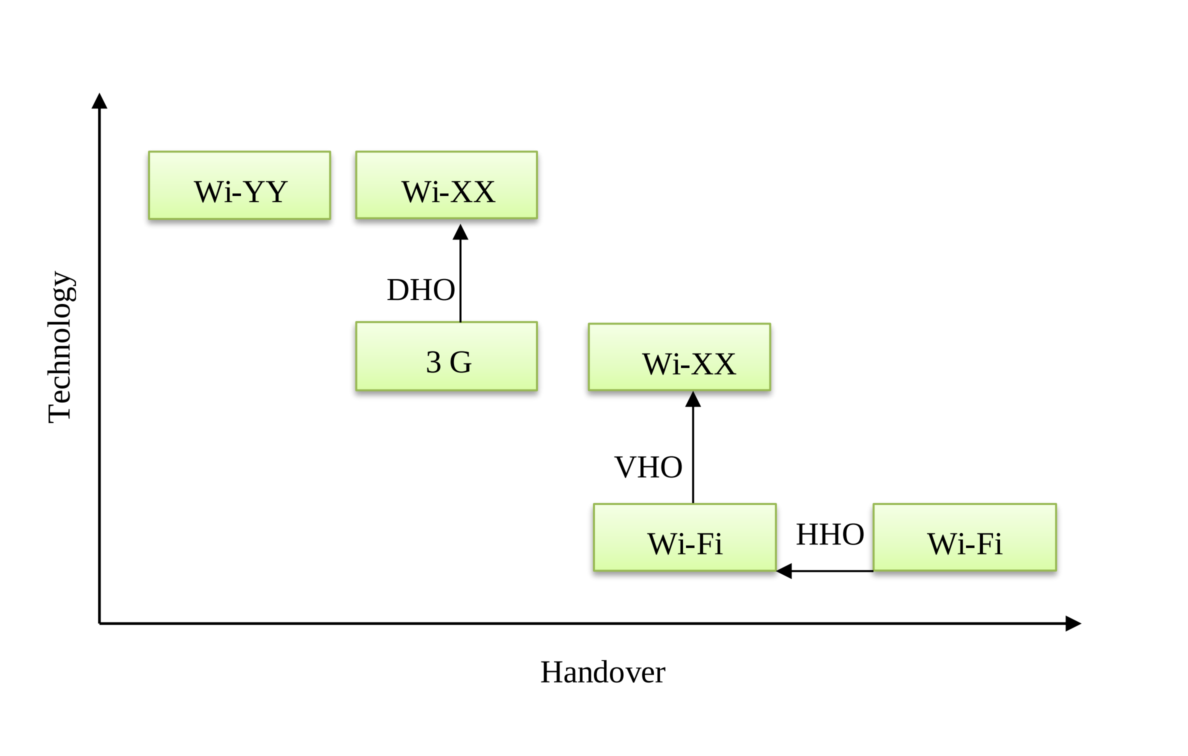

Figure 2-4: DHO, HHO and VHO

2.3.3 Vertical and Horizontal Handover

As previously mentioned, a HO is the process that enables users to keep the connection when their STAs change the joining point to the access network, also known as the 'point of attachment' [5]. The handover classification depends on the access technology, i.e., whether it is the same technology or different. Table 2-2 illustrates the main differences between horizontal and vertical Handovers in terms of the handover consequence.

Table 2-2: Difference between VHO and HHO [8]

	VHO	HHO
Network Connection	More than one connection	Single connection
QoS Parameters	Maybe changed	Not Changed
Access Technology	Changed	Not Changed
IP Address	Changed	Changed
Network Interface	Maybe Changed	Not Changed

2.4 Handover Phases

Several studies have revealed that HOs could be divided into three phases, HO Information Gathering, HO Decision Making and HO Execution [28], [24], [29]. We will describe these three phases in the following sections, which all together are called Handover Management.

2.4.1 Handover Information Gathering

The first phase, also known as system discovery, focuses on collecting information in order to identify the need for a handover, and can subsequently initiate it. The HO process usually uses the IEEE 802.11 standard during this phase to obtain information by such as RSS, available BW, jitter, delay [10]. The full set of information gathered will help make the best HO decision [20]. This phase aims to gather all the available information by a mobile device that will scan the surrounding networks to detect all the possible services, data rates and power consumption. Other collected information on a mobile device is also needed, such as device features, speed and battery status. Table 2-3 shows the required information and parameters for the HO process from each network layer.

Table 2-3: Information parameters pertinent to the HO process

Layers	Type of Parameters
Application	Context information (e.g. speed) User preferences (e.g. cost, provider), QoS parameters (e.g. offered bandwidth, delay, jitter), security alerts (e.g. notifications)
Transport	Network load (e.g. available BW)
Network	available foreign agents, network pre-authentication, network configuration, network topology, routing information
Data-link	Radio access network conditions, link parameters, link status
Physical	Available access media, for example copper or fibre, WLAN

2.4.2 Handover Decision Algorithms

The second HO phase focuses on providing user satisfaction by trying to determine the most appropriate access network. The information gathered, based on the aforementioned parameters, is used to make the HO decision. The decision step is highly critical during whole HO process as it is responsible for deciding at what time to start the HO process and to which AP the connection should be made. The HO process has a different level of complexity in homogeneous and heterogeneous networks, i.e. with the same or differing physical technologies. In homogeneous networks, the timing of HO is decided based on the RSS values while the selection of best AP is primarily trivial due to having the same network. However, in heterogeneous networks, the HO process is non-trivial which naturally increases the complexity.

Making a HO decision is a challenging task, and there are many approaches that have been proposed in the literature. These approaches can be divided into the following two categories: static and dynamic. Static approaches focus on the user profile [10], whereas dynamic approaches focus on the Mobility and RSS [4]. Many works classify handover decisions into the following seven strategies detailed in the next subsections [21][10]:

- Received Signal Strength (RSS)
- Decision function-based algorithm strategies (DF)
- QoS and User-centric algorithm strategies (UC)
- Multiple attribute decision algorithm strategies (MAD)
- Fuzzy logic and neural network-based algorithm strategies (FL/NN)
- Cooperative Vertical Handover strategies (CVHO)
- Context-aware algorithm strategies (CA)

2.4.2.1 Received Signal Strength

Traditional HO decisions are based on RSS and a hysteresis margin [21]. The RSS represents the strength of the radio signal received by the STA. The idea behind RSS-based algorithms is simply comparing the RSS of the current attachment point with the RSS of the other available networks, while the hysteresis margin value is considered in order to avoid the ping-pong HO. Ping-pong HO happens when the STA hands over from one AP to another but rapidly hands back to the original AP, and that will cause unnecessary HO signalling messages. The STA scans the surrounding networks, checking the availability of each candidate wireless network during the discovery phase. After that, the STA measures the level of the RSS of each network and compares the RSS of its currently connected network with the new one. If the new RSS is higher than the current one, the handover process moves the STA to the new network. Otherwise, the process goes back to the network discovery phase [21], [27]. The general steps of the RSS-based algorithm are shown below.

1. RSS only: choosing the new Base Station (BS), if $RSS_{new} > RSS_{old}$.
2. RSS with Threshold T: choosing the new BS, if $RSS_{new} > RSS_{old}$ and $RSS_{old} < T$.
3. RSS with Hysteresis H: choosing the new BS, if $RSS_{new} > RSS_{old} + H$.
4. RSS, Hysteresis and Threshold: choosing the new BS, if $RSS_{new} > RSS_{old} + H$ and $RSS_{old} < T$.

This criterion is suitable to determine the time of HO. However, the limitation is that it does not involve user intervention according to their preferences. Therefore, more efficient criteria are required to take into account user preferences. Additionally, as data traffic increases due to a large number of devices connecting to the network, WLAN networks provide multiple APs to support traffic growth by using a method called network densification. This method allows providers to increase the data traffic with the help of reusing spatial spectrum. However, due to many small cells with multiple APs, the possibility of a handover will gradually increase. The hysteresis margin minimises the effect of the ping-pong HO with reasonable handover overhead. To further improve the handover process, the method of adaptive hysteresis margin is utilised which exploits the velocity of the STA and the radio channel in order to self-optimise the hysteresis margin during handover decision making [30].

2.4.2.2 Decision function-based algorithm strategies (DF)

In general, the HO decision function can be based on both the cost function and utility function. Usually, a DF strategy includes the sum of the weighted function of some parameters, such as monetary cost, QoS, trust, preference, compatibility and capacity parameters. The general formula for the cost function of a wireless network is:

$$f_n = \sum_s \sum_i w_{s,i} \, . P^{n_{s,i}} \qquad 2.1$$

In equation 2-1 $p^{n_{s,i}}$ is the cost of the i-th parameter to carry out service S on network n, $w_{s,i}$ is the weight (importance) assigned using the i-th parameter to perform the services [21].

The network with the lowest cost is then chosen as the target network. Therefore, this cost function-based policy model estimates dynamic network conditions and includes a stability period (a waiting period before handovers) to ensure that a handover is worthwhile for each STA. In [31] the authors proposed a VHO Decision Function-based algorithm that relies on a cost function that first checks all available networks, and then calculates the cost of each of them, focusing on battery consumption, bandwidth and network delay. The algorithm chooses the network that offers the highest service at the lowest cost. The Generalized Mechanism of Decision Function-based strategies is presented in Figure 2-5[27] [31].

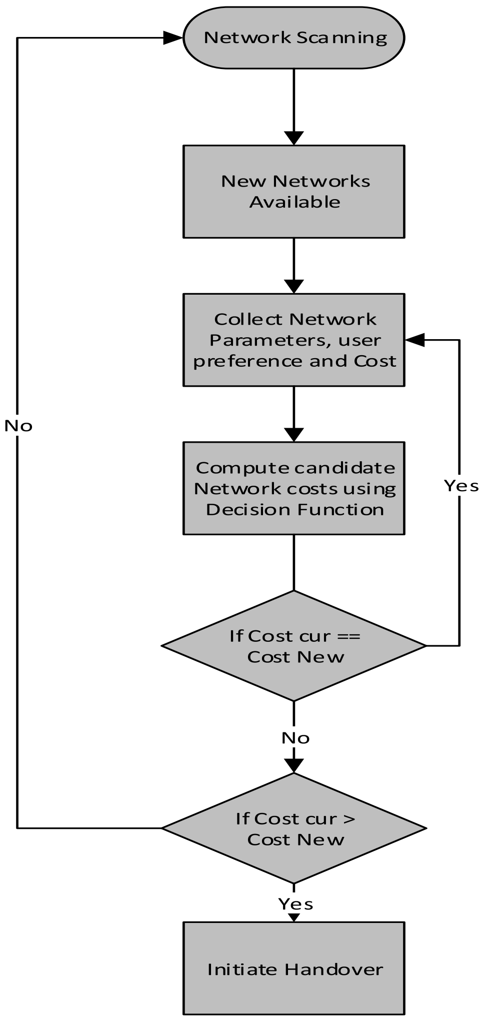

Figure 2-5: Generalized Mechanism of Decision Function as in [31]

The second decision function is based on the utility, which is the level of accessibility of the service in the network. The main measure in this algorithm is the users' satisfaction related to different properties of the network [27]. An average data rate has been proposed in [32]. In detail, this technique utilises a utility function for each candidate network and its available resources at the first phase of the scheme, which is the scanning phase. Based on this, a relationship can then be established between the resulting utility function and resources, which allows the mobile users to make a handover decision and a network selection. It is important to consider that these schemes do not necessarily always guarantee a network selection. This is due to the fact that utility-based schemes are not as independent as the considered criteria.

2.4.2.3 QoS and User-centric algorithm strategies (UC)

In these strategies, the HO decision takes into account different features like bandwidth, cellular cost, and coverage area. In [27] they divided QoS into the following three main categories in order to make the optimal decision: user profile, available bandwidth and Signal-to-Interference-Noise Ratio (SINR) as explained below.

- **User profile:** In order to reach end-to-end seamless mobility with QoS assurance for the clients, Calvagna et al. [33] proposed vertical HO strategies where the decision was based on user preferences such as QoS and cellular monetary cost. In detail, two HO schemes have been presented among GPRS and WLAN. In [5] the authors propose an HO decision that considers the expected completion time of data transfer, and the consumer surplus, which is the difference between the actual price charged and the monetary value of the data transferred.
- **Available bandwidth:** This HO strategy is based on finding the optimum user preference in terms of available bandwidth [34]. As an STA connects to one of the available WLANs, the proposed scheme firstly checks the level of RSS at the STA, which is compared with a predefined threshold. The HO is performed to another preferred network only if the new network provides higher bandwidth.

➢ **Signal-to-Interference and Noise Ratio (SINR):** The SINR is defined as the ratio of the power of a certain signal of interest to the sum of the interference power which comes from other interfering signals and the power of some background noise**.** In [27] the authors rely on the SINR computation to check the performance of the system based on the throughput by using the following equation:

$$R = B * log_2(1 + SINR) = B * log_2\left(1 + \frac{Y}{N}\right) \qquad 2\text{-}2$$

Where B is the channel bandwidth, R is the maximum achievable data rate, N includes the overall interference and the noise power and Y is the overall received signal power through the bandwidth. This mechanism based on QoS is presented in Figure 2-6.

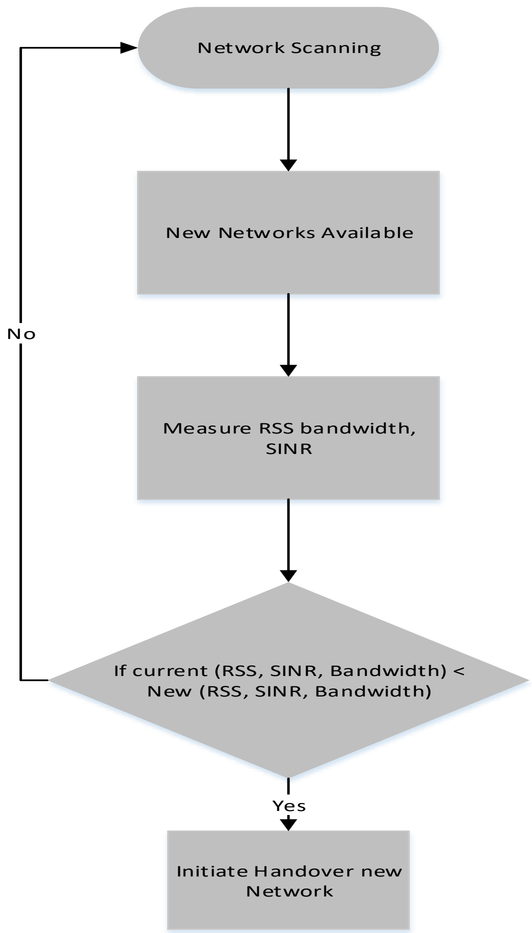

Figure 2-6: Generalized Mechanism of QoS-based Schemes

2.4.2.4 Multiple Attributes Decisions (MAD) strategies

In these strategies, a selection is made from a limited number of candidate networks, depending on different criteria such as Multiple Attributes and Multiple Objectives [2]. Work presented in [27], [35] classifies MAD strategies into three categories as follows:

- **Grey Relational Analysis (GRA):** Generally, this technique will grade the nominee networks, and the highest rank from the list will be chosen as the best candidate network.
- **Technique for Order Preference by Similarity to Ideal Solution (TOPSIS):** This technique also lists the nominee networks, and the decision algorithm will choose the closest network to the ideal solution avoiding the poorest case solution.
- **Simple Additive Weighting (SAW):** In this technique, the algorithm will calculate the weight of all attributes, in order to sum up to the overall score, then the highest score will be chosen.

In terms of network selection techniques, a combination of GRA and TOPSIS techniques can be used to find a trade-off between network conditions, service application and user preferences [21], [36]. Generally, there are three logical function blocks within these techniques that start by collecting data, then process such data, and finally make a decision based on the obtained data. In these works, the results for UMTS/WLAN system revealed that the combination of these techniques can work efficiently. The limitation of the GRA, TOPSIS and SAW algorithms is because of the complexity of bidding adjustments in the handover process which introduces delays during the handover decision making phase.

2.4.2.5 Fuzzy logic and neural network-based algorithm strategies

Another HO category found in the literature uses Fuzzy Logic Control theory (FLC) in the decision making process [10]. In this category, the FLC HO algorithms are characterised by the capability to monitor and analyse different parameters such as RSS, load and bandwidth in the case of both real-time and non-real-time applications. For instance, FLC HO algorithms through this capability, combine different attributes with multiple criteria providing the best AP selection as proposed in [37]. Further, the authors use imprecise information along with user preferences for making the decision of an efficient HO. The imprecise information includes price, bandwidth, SNR, sojourn time, seamlessness and battery consumption while the user preferences are the weights assigned for services such as voice and file download. The FLC algorithm consists of three steps. In the first step, the imprecise information and the user preferences are fed to the fuzzifier which converts data into either fuzzy, crisp or fuzzy and crisp. Then in the second step, the inference system utilises the rules from the knowledge base and provides a decision in the form of fuzzy logic (e.g. degree of being true). Finally, in the third step, the defuzzifier provides quantifiable output in the form of crisp logic (e.g. Boolean logic) which is finally used for the HO. The authors in [38] and [39] proposed a multi-criteria HO decision based on FLC and neural networks. Specifically, they used a neural network to analyse the FLC parameters (e.g., RSS, network load and the distance between STAs and cells) in order to obtain the optimal HO decision. The authors categorise parameters into three types as network-specific, user-specific and device related parameters. A large number of parameters allows for making better HO decisions. The network related parameters are usage cost, network security, transmission range and the capacity while the user related parameters include network conditions and energy consumption. The authors include device related parameters to provide support for compatibility issues and other technical information. Additionally, the authors exploit the capability of the neural network in terms of processing a large number of parameters to make an efficient HO decision.

2.4.2.6 Cooperative Vertical Handover Strategies

The traditional HO struggles to offer a good quality of service due to the lack of intelligence, which causes delays as well as a packet loss. Recently, solutions have proposed to address the seamless VHO challenge using a cooperation technique. In [25] and [15] for instance, the authors propose the deployment of an agent into APs and STAs to gather information from the environment in order to make the best decision in a seamless way. The authors of [25] claim that using an agent will reduce the packet loss and latency in the HO process. The agent takes into account all the possible elements such as network coverage area, network security bandwidth, QoS, network load, monetary cost and user preferences. Therefore, it cooperates with STAs and APs to select the best network depending on all these factors. In fact, the preferences of users are the most important factor in this case. Work in [40] proposes a mobile agent relying on a decision-making mechanism including three phases as follows: a) context management framework, b) programmable platform, c) service deployment. The first phase aims to gather information from different networks, the second phase involves choosing the best modules to employ, while the last phase consists of managing the work of the agent on the mobile.

2.4.2.7 Context-Based Vertical Handover Strategies

Context-based schemes can rely on any information that is pertinent to the situation of an entity (person, place or object) [27]. This concept is based on the information gathered from the network and STAs in order to make better decisions [41]. Crucial to this strategy is the evaluation of the change of the radio environment context and the management of the gathered information in order to make the optimal decision on whether or not it is necessary to switch to the next candidate. The author in [8] has divided context-based schemes into the following four categories below:

(i) **Mobile Agent-Based Schemes:** In this scheme, a programmed agent is located on a programmable platform that is responsible for installing the appropriate modules for contextual exchange. In [42], the authors propose a mobile agent that could offer a distributed HO decision. Specifically, the author presented the following three types of agent: multi-access provider (MAP), wireless provider agent and terminal device agent. The main function of a MAP is to support the activity of other agents in both the STA and wireless networks. The MAP usually runs two types of agents on the STA, which includes a profile agent that is responsible for checking application needs and QoS. The second agent is the connection manager agent, which is responsible for execution [8]. The author demonstrated that there are many advantages of using this method, such as intelligent context collection, optimised blocking rate, as well as being able to adapt to a variety of wireless network connections. However, many issues as a result of using this method can also occur. For example, large numbers of agents are needed, and there is also increased communication overhead, high handover latency and issues about deployment in the real world.

(ii) **Context-Aware analytic hierarchy process (AHP):** This technique breaks down the problem of HO selection into a number of sub-problems, where each sub-problem will be assigned a weight value. Breaking down the problems will give more accurate results in terms of the HO decision, which will give the highest QoS that satisfies the user requirements. In this scheme, a predefined objective-based handover decision and network selection are carried out with the help of a scoring mechanism and merit functions. This strategy could improve performance in terms of power consumption, network revenue and HO drop rate [15]. In [40], the author presents a case study for the HO between WLAN and UMTS using a AHP strategy. This study presents a flexible, efficient and seamless HO decision. In [43] the authors present another VHO method based on AHP to enhance the QoE and QoS. The authors consider the evaluation of both the network and STA by using a merit function. The priority in this method focuses on user preferences. Moreover, modifying QoS monitoring is combined with the merit function to cut down power depletion on nodes [27]. This scheme has benefits in terms of improving HO latency, throughput and packet loss. However, there are some limitations of this scheme which include a lack of intelligence in the HO process and high resource consumption.

(iii) **Context-Aware Cooperation Scheme Media Independent HO (MIH) Based Context-Aware Scheme:** The author in [44] employs the cognitive cycle to include in the handover process adaptability, cognisance and seamless HO. The authors divide the mechanism into the following four functions:

a. Context Acquisition Function (CAF): this function is responsible for gathering the information related to the radio resources.
b. Context Information Provider (CIP): this function is responsible for gathering the necessary information about the user location and end-users to support mobility management.
c. Context Matching: this function combines CIP and CAF to reach an optimal QoS based on user preferences and application.

d. Mobility Management: the last function is responsible for the execution of a seamless HO.

These functions prepare the STA to quickly switch to suitable networks with better QoS. The authors claim that the techniques are scalable due to using advanced resource allocation, which enhances user experiences [20]. There are many advantages of using context-aware cooperation, one of them is the distributed HO decision, which is more efficient. Moreover, it provides improved QoS with respect to bandwidth for example, which makes it more suitable for real-time streams. However, this method could cause a security provision issue, as well as a higher packet loss and high signalling cost. Another issue faced by this scheme is the increased complexity during HO.

(iv) **Media Independent HO (MIH) Based Context-Aware Scheme**: This scheme uses a technique that again collects information from both the client and the network but also stores their neighbourhood information. This method uses link layer intelligence to carry out a cooperative HO decision. The MIH function provides a variety of services to the STAs by utilising different interface layers (lower and upper). Details of these services are outlined below [27]:

a. Media Independent Event Service (MIES): this service is responsible for gathering information network Status and provides a variety of triggers such as quality link status.

b. Media Independent Command Service (MICS): this service is responsible for the network reconfiguration at the high-level layers by a set of comments and manages the lower layers.

c. Media Independent Information Service (MIIS): this service is responsible for discovering the neighbourhood networks using MAC address and channel information.

Finally, MIH is defined as a distributed HO decision due to the use of predefined triggers that consider application and users. This reduces the latency of HO with optimal network selection and less packet loss. However, this scheme is valid in a simple scenario with a limited number of connected users and does not work well in large scale scenarios because it includes high resource consumption with supplementary signalling such as overhead messages.

2.5 Limitation of Current Handover Techniques

As we have explained in chapter 2, the state of the art presents different techniques addressing HO decision making. On the other hand, the existing HO methods do not meet the requirements of STA applications, due to the lack of intelligence of current networks, especially considering the massive increase in mobile devices and the evolution of applications. Our literature review also shows that although there exist many works addressing HO, these contributions are proposed with the assumption that the wireless network is small in size implemented in a simple scenario with a very limited number of users. However, in the near future, wireless networks are expected to become more dense due to the increasing number of mobile devices such as laptops, smartphones, tablets as well network providers [3], [45]. Moreover, the variety of wireless network technologies such as wireless metropolitan area network (WMAN), WLAN and cellular (3G or 4G) makes the network environment a much more complex structure. Note also that, according to [46], the delay in the current standard HO process is up to 2 seconds, which is not tolerable for applications such as Voice over IP and Video Streaming.

Furthermore, Quality of Experience (QoE) recently became a common metric to measure user satisfaction [47]. The QoE represents the measurement of network system performance as perceived by the user. Therefore, QoE also needs to be considered when designing HO strategy in order to reach satisfactory services for the users.

The HO is, therefore, a challenging task, especially in the case of real-time applications that require large amounts of data such as live videos streams. We can summarise the limitations of the current HO strategies found in the literature as follows:

- **Lack of QoS and QoE Awareness:** Many of the HO approaches found in the literature focus on the process of moving the device from one network to the other, while neglecting the effect of such process on the service provided to the STA. Such limitation results from the lack of awareness of the requirements of the STA as well as the limitation of the monitoring process.
- **Complexity and Lack of Flexibility:** Although certain existing HO solutions are able to capture the performance requirements of the STA, the implementation of these solutions often results in high density. Moreover, such approaches, which focus on a specific performance metric and a specific wireless technology, cannot be adapted to support other performance metrics or work on different wireless technologies.
- **Scalability:** Most of the HO solutions found in the literature are distributed where only the IEEE 802.11 AP and the STA are involved in the process. Although these approaches could provide good performance in small size networks, they do not scale well with the size of the network. This is particularly important in the large WLAN that we see deployed today in university campuses and public spaces.

We believe that these limitations could be addressed by introducing centralised and intelligence controller into the network that will assist the HO process and add the QoS and QoE requirement. SDN is a promising model for centralised yet scalable management of networking resources and operations. Therefore, this intelligent network will be built using the centralised SDN concept, where the SDN controller is the central entity that can monitor the performance of the Large network and in which the HO algorithms will be implemented.

2.6 Quality of Experience (QoE)

QoE in this context can be defined as an overall measurement of the network system performance, which depends on the perceived acceptability of service from the user's point of view. For instance, the Mean Opinion Score (MOS) is a QoE metric providing the human user's view of the quality of the network [48]. Specifically, the MOS is an arithmetic mean of all the individual scores achieved by the result of subjective tests and can range from 1 (worst) to 5 (best). Herein, the MOS provides a quantitative analysis of the more general form of QoE whereas the QoS is the actual bandwidth offered by the network to the user. The meaning of each score is illustrated in Table 2-4 in terms of quality and impairment. Specifically, the qualities range from Bad, which corresponds to a Very Annoying impairment to Excellent that corresponds to an Imperceptible impairment. An extended QoS to QoE mapping will be described in Table 6-1.

Table 2-4: Mean opinion scores and corresponding Qualities, Impairments and Video

MOS	Quality	Impairment	Video 720p, 24fps
5	Excellent	Imperceptible	>9 Mbit/s
4	Good	Perceptible but not annoying	5.8-9 Mbit/s
3	Fair	Slightly annoying	4.5-5.8 Mbit/s
2	Poor	Annoying	3.4-4.5 Mbit/s
1	Bad	Very annoying	3.4 Mbit/s

2.7 Summary

In this chapter, we presented different research works regarding the HO, resource allocation and mobility management in both homogeneous and heterogeneous wireless networks. Our narrative starts with a background to introduce IEEE 802.11 and the deployment of WLANs. Then we explained the techniques in vertical and horizontal HO. Moreover, we explained the typical HO phases which are the information gathering phase, decision phase and finally the execution phase. Then, we discussed the existing solutions in this area in detail, and finally, we explained the limitations of the current existing HO techniques and solutions, and how this limitation could be addressed by introducing a centralised intelligence into the network that will assist the HO process and add the QoS and QoE. This centralised approach will be based on SDN. The following chapter will present existing mobility management approaches in distributed and centralised network architectures. Furthermore, we highlight the limitations of a distributed network architecture and indicate the need for centralised mobility management. Finally, we will introduce the SDN and SDWN concept and we will present our proposed architecture based on this approach.

Chapter 3 Problem Formulation and Proposed Architecture Design

3.1 Introduction

As shown in the HO literature review, existing HO solutions exhibit a number of limitations that affect the performance of mobile devices and ignore their requirements [22], [23]. These issues are caused by a lack of awareness within the wireless network of the performance requirement of the users' devices, the distributed nature of most handover solutions, and their density and poor scalability. Therefore, this chapter will discuss existing distributed and centralised approaches for mobility management. Subsequently, it will show the limitations of distributed architectures that dictate the importance of a centralised network and introduce SDWN as a promising model for the centralised approach.

3.2 Mobility Management and Handover limitations in IEEE 802.11

Due to the rapid growth of IEEE 802.11 wireless LAN users and their mobility, new concerns are emerging related to the high throughput demanded by the end users, the quality of service (QoS) and the need for a seamless handover during the movement from one AP to the other and load sharing. As a result, it is observed that the ubiquitous delivery of rich internet services requires efficient and cost-effective mobility management. The traditional IEEE 802.11 technology has fundamental limitations which make the wireless infrastructure challenging during the period of handling control between multiple APs. The major limitations of traditional standards IEEE 802.11 technology are discussed below [49].

3.2.1 Tightly coupled infrastructure

In the traditional IEEE 802.11 infrastructure, the control layer and the data layer are tightly coupled together. 802.11 works on two layers of the OSI model i.e. the data link and physical layer. The data is formatted in these layers and controlled in order to conform to 802.11 standards. As a result, the control of the network and data transformations are integrated together in 802.11 networks. This poses a problem during the integration of new services and applications in the network. Eventually, it becomes challenging to implement efficient handover algorithms for mobile users which are based on the real-time network state.

3.2.2 Centralised mobility management

Traditional IEEE 802.11 technology-based APs do not provide support for centralised mobility management during the handover process even when proprietary solutions are used. For instance, in Cisco centralised network mobility management is provided when users switch APs and load balancing is achieved in terms of finding optimised routes between APs which is in contrast with the load balancing in users' handover process. Additionally, when users move from one AP to the other, they go through a process of authentication before using the services of new AP. This authentication process for the new AP adds an extra overhead. This overhead has less impact when the user is idle. However, during a VoIP call or while using time-constrained services, the authentication process has several effects such as the user loses the connection if the authentication process takes a long time.

3.2.3 Signal interference among APs

Areas with a high density of users require multiple APs in order to provide seamless services with the perfect connection to the users during mobility. STAs using the IEEE 802.11 standards scan the network and receive a list of available SSIDs. The STAs connect to a particular SSID based on the signal strength of that AP which is known as RSSI. However, this causes the signals from multiple APs to overlap with each other which results in decreasing the throughput due to the loss of data packets. Wi-Fi technology lacks the capability of load sharing and develops imbalanced networks. This results in inefficient use of Wi-Fi network resources.

3.3 Distributed and centralised mobility management approaches

Currently, two approaches i.e. distributed and centralised are adopted for control and wireless network management. The mobility management solutions in flat and decentralised IEEE 802.11 Wi-Fi technology-based networks are carried out using a mobility anchor. The purpose of the mobility anchor is to track the location of the mobile user and tunnel the traffic to a predefined Wireless LAN Controller which is specific to that network. When a mobile user moves around from one AP to another, the previous traffic route is preserved in order to prevent a reconnection delay [50]. The mobility management approach based on mobility anchors has some drawbacks. However, the mobility anchor can become a barrier in the case of a large data transmission which causes degradation in QoS for the mobile users. Another problem encountered by mobility anchor is the single point of failure. If the mobility anchor stops functioning or there is a cyber-attack, the service to all the mobile users gets affected.

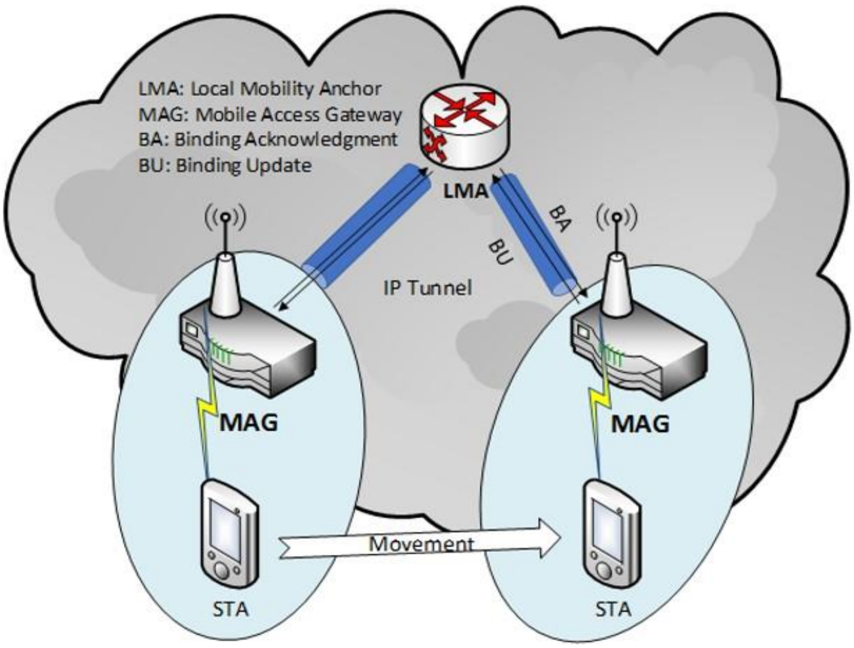

Figure 3-1: Mobility management in PMIPv6

In distributed networks, two types of mobility management methods are used. One method is based on specific protocols such as MIPv4/MIPv6/DSMIPv6/PMIPv6 [51]. In this approach, location messages are transferred between the mobility anchor and the mobile users through Mobile Access Gateway (MAG) as shown in Figure 3-1. Tunnels are used to provide communication services between the mobile user and the mobility anchor. The tunnels work as channels to encapsulate all the data traffic and communicate between two nodes in the network. During the movement, the mobile user's previous address is mapped to the new proxy address by the new AP. The binding between two addresses which are from home network and the new foreign network allows rerouting of the traffic to the mobile user in the new network.

The other method is based on the HIP, SMIH6, LISP [52] and is also known as the Identifier / Locator separation technique. Mobility management is enabled here by updating the protocol stack at the mobile users and the routing tables. This approach utilises two namespaces to specify the location and identity of the mobile user i.e. Route Locator (RLOC) and End-point Identifier (EID) as shown in Figure 3-2. A database is used to provide a mapping between

RLOC and EID. In the first approach of mobility management, mapping is provided between the actual IP address while in the second approach the location information is separated from the identity and mobility is managed through the location information. The existing distributed frameworks and methods developed for mobility management basically separate the location and routing to different entities in the network.

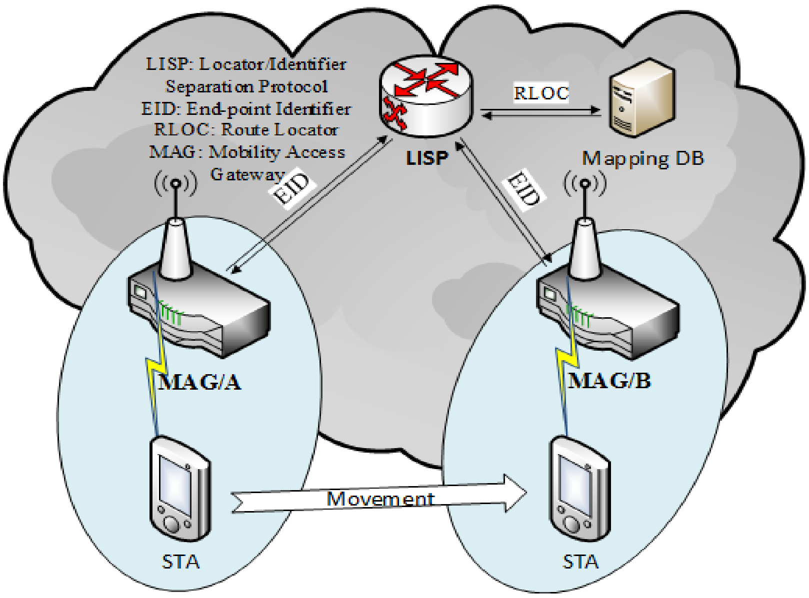

Figure 3-2: Location-based mobility management approach

Due to certain problems, these frameworks which are based on the above methods, i.e. MIPv4 or HIP, are still not used in their full extent. For instance, they require the active participation of a mobile user during mobility management and add new software, which can affect the energy consumption of mobile devices. Another problem is the increase in complexity of the handover mechanism. In a distributed network, a delay in the handover can occur due to the excess of messages between the mobile devices and the network. Though the IEEE 802.11 Wi-Fi standard allows the embedding of additional software or optimisation algorithms for mobility management, the limitations in the processing capabilities of Access Points and information about the network restrict deployment of efficient mobility management approaches.

On the other hand, the methods based on centralised paradigms are either vendor-specific or do not provide full capabilities for network management. The drawbacks of existing approaches demand a novel mobility management architecture that allows mobility management flexibly and optimally with the assistance of an open programming interface and enables network administrators to develop new Radio Resource Management (RRM) solutions [53].

Fortunately, emerging solutions based on SDN provides similar functionalities such as programmable routing to traditional wired networks. As such, SDN provides a promising approach to solve the problems of mobility management, which separates the control layer from the data layer in the network. The control layer provides the functionality to monitor the location of mobile devices and update the routing tables directly without exchanging lots of messages. Consequently, this could significantly reduce delays in the handover process. Another major benefit of SDN based mobility management is that it does not involve the mobile devices in HO decision making process, thus reducing the complexity and the requirement for new software in every terminal. The proposed approach takes the benefits of SDN technology in terms of separation of the control layer and data layer with the centralised controller and enables efficient handover during mobility management. The centralised controller performs heavy processing of switching users between APs and removes the communication overhead burden from the mobile nodes. This provides the benefit to the mobile devices in terms of seamless handover, better QoE and long battery life with less power consumption.

3.4 Software Defined Network and Software Defined Wireless Networking

This section will explore the SDN and SDWN concept along with OpenFlow and the use of wireless virtualisation. Additionally, we will explain some current SDN-based mobility management techniques in this section.

3.4.1 Software Defined Networking Model

Software-Defined Networking (SDN) is a networking paradigm that promotes the separation between the control plane and data plane, thus, allowing the centralisation of network management into a single entity[54]. As illustrated in Figure 3-3, the SDN controller is able to program data plane switches and implement different networking policies using an application programming interface, which is often supported by the OpenFlow protocol [55], [56]. OpenFlow is considered one of the first SDN standards that define the communication protocol in SDN environments that enables the SDN Controller to directly interact with the forwarding plane agents.

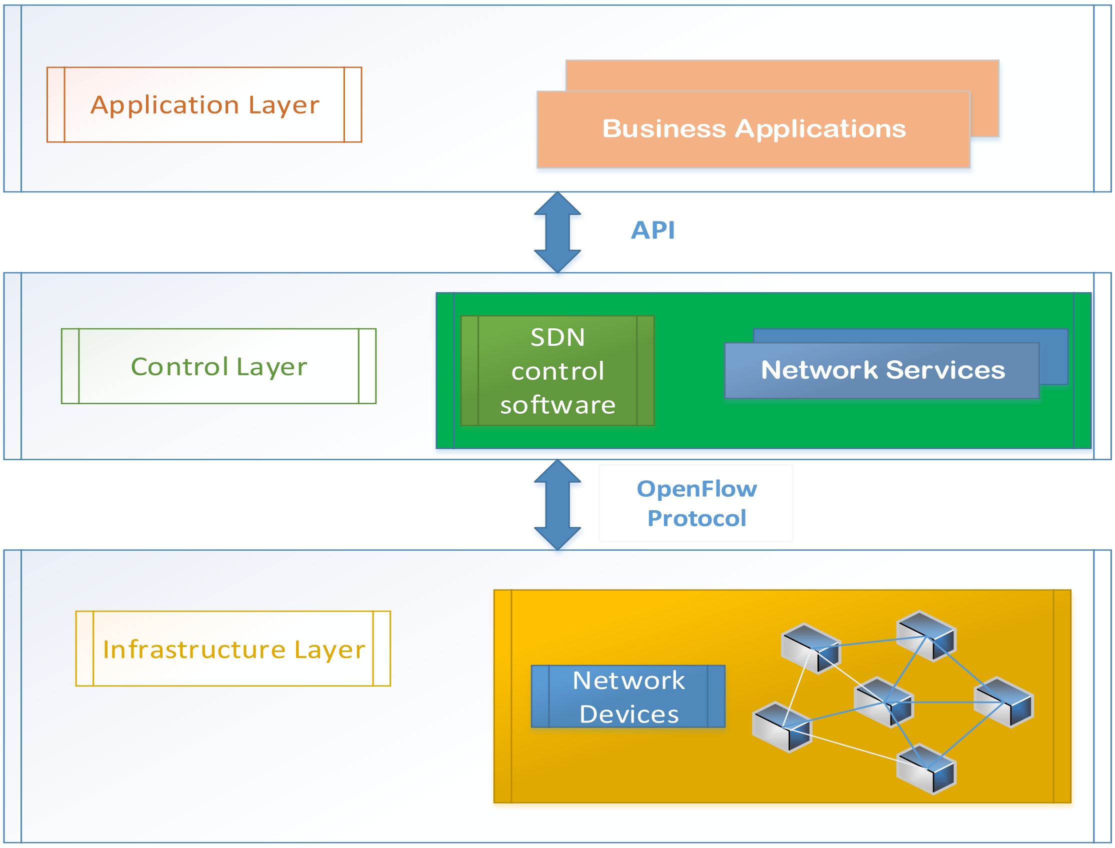

Figure 3-3: General Representation of the SDN Architecture

SDN exhibits certain features that make it an attractive approach to address the seamless mobility challenge, such as reduced network complexity, granular network control and improved scalability.

One of the main features of SDN is its monitoring and measurements functionality. SDN offers flexibility and reliability in terms of network monitoring, which is also a key component in the HO as part of the information gathering phase [57]. The methods of traditional monitoring and measurement are divided into two techniques, Passive and Active. Passive techniques will measure the network traffic by observation only, while Active methods measure the traffic by injecting additional packets into the network and monitoring their behaviour [19]. In the specific case of SDN, the controller receives per-flow monitoring statistics through OpenFlow [58], which is a protocol used as an interface between the control plane and data plane. This allows the SDN controller to have an overall vision of the network and all the flows, which makes the monitoring more effective and could help improve the performance of HO in wireless networks.

For example, in [57] the authors propose an extendable and flexible network monitoring framework by using a generic RESTFUL API, which gives a higher accuracy of the statistics of the network per-flow for seamless HO strategies. Therefore, using OpenFlow will give the possibility to monitor and measure all the flows, and increase the controller awareness of each flow requirement in terms of QoE or QoS [59].

OpenFlow is one of the main protocols used to interface the data plane and control plane. The main feature of this protocol is the flexibility of programming the packet forwarding tables, allowing programmers to control the flow tables in OpenFlow switches in order to manage the network resources. The idea of the OpenFlow switches is to give full responsibility to manage the data plane to the controller, while the OpenFlow switches manage the data plane by dropping or forwarding packets according to the flow table. Each flow table has a set of actions, counters and match fields. The set of actions is responsible for handling the packet flow, while the counters are responsible for providing the monitoring and measurement statistics. Finally, the match fields are used to match against packet header fields [60]. Table 3-1 illustrates OpenFlow match fields. Each OpenFlow switch has a predefined match field compared with every received packet [61] in order to take a decision, such as forwarding or dropping the packet. There are many types of tools used for OpenFlow based controllers, such as OpenDaylight [62], beacon [63], NOX [64] POX [65] and Floodlight [66].

Table 3-1: OpenFlow Match Fields

Ingress port into OpenFlow switch	Ethernet source address	Ethernet destination address	Ethernet segment type
VLAN identifier	VLAN priority	IP source address	IP destination address
IP protocol	IP type of service	TCP/UDP source port	TCP/UDP destination port

3.4.2 Software Defined Wireless Networking (SDWN)

To date, SDN has been used in many environments, however, it took many years to deploy SDN also in a wireless environment. This is because the wireless network environment is more challenging than many wired networks due to the dynamicity issue of interference between the signals, which requires more control traffic [59]. Moreover, the increasing consumption of data is directly proportional to the increase in users and the quality of the application.

Using SDWN provides the wireless network with more flexibility and ease of use for instance in terms of load balancing, STA traffic awareness and handover management. These services could be provided by one of the SDWN framework programmable WLANs such as Odin. Odin [67] is an architecture and set of technical instructions based on open industry standards, which describes best practices for developing virtualised, converged wireless network. Odin provides virtual machine mobility, automated management of SDWN systems maximising high-availability, energy efficiency, and scaling of networks to thousands of physical devices without over-subscription, which will reduce the capital and operating expense by 15% - 25% according to [68]. Furthermore, Odin allows wireless network operators to provide services to the users as network applications through the Light Virtual AP (LVAP) abstraction [53]. Figure 3-4 shows the Odin architecture.

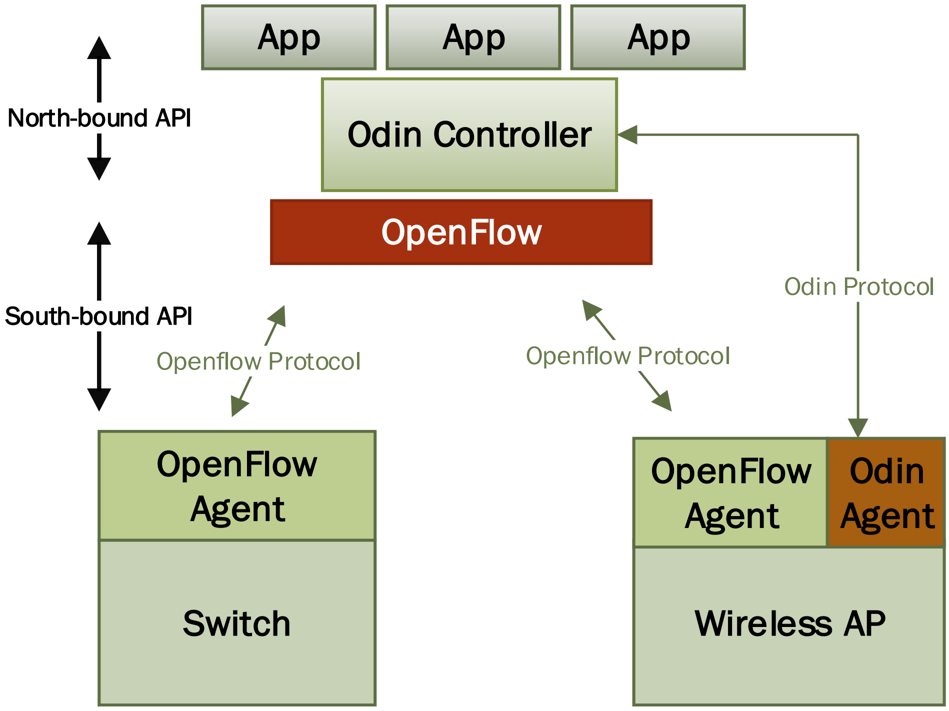

Figure 3-4: Odin Architecture

The Odin architecture involves the following three main elements: a controller, a set of applications and multiple agents. The controller is placed on the top of OpenFlow and has a global view of the WLAN to manage application flows [67]. The APs and switches will be run by Odin agents using the OpenFlow protocol. Those agents could be installed in any supported APs or Switches such as Netgear R6100 and TP-Link Archer which is required to design new hardware. Below the Odin elements are defined:

I. **Odin controller:** The controller maintains a view of the whole network and enables network applications to programmatically orchestrate the underlying physical network[69]. It exposes an interface to the application layer through the north-bound API that allows applications to programme the controller, for instance, changing HO policy, then the controller will interpret the commands to the agents via the south-bound API.

II. **Odin Agent:** The agent is deployed and run on each AP. It provides an interface between the controller and the AP and performs functions, such as monitoring, and reporting measurements collected from the AP to the controller every 0.02sec as an interval time.

III. **Application:** the applications in Odin could work ether reactively such as with a Handover or proactively such as for load-balancing by accessing statistics from different layers such as OpenFlow statistic and the statistics collected by the agents.

Additionally, the author in [70] proposed the Light Virtual AP (LVAP) abstraction for the first time. The idea of the LVAP is to establish a continuing connection between flows and APs by creating a separate LVAP for each AP using a unique BS SSID. The benefit of using this unique SSID is to avoid re-association. Figure 3-5 shows the LVAP concept.

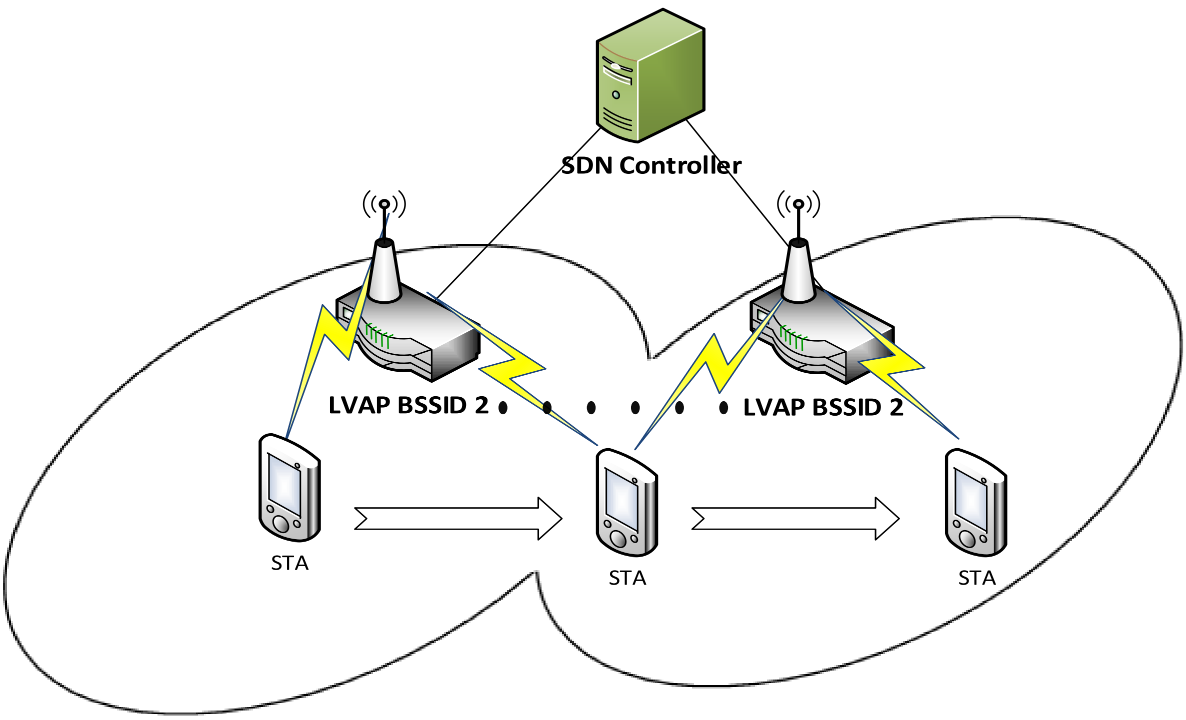

Figure 3-5: Light Virtual AP

The author in [64] introduced Network Virtualisation as a technique that allows separating traffic flows into separate subspaces to share the network resources. This could also be called network slicing. Many slices or subspaces can run on one device. Recently, many SDN works support the slicing concept directly such as FlowVisor [71] and Open Visorx [72]. In [71], the controller creates a layer between the data plane element and the control plane in order to have multiple controllers on a single shared data plane.

Finally, the author in [72] has introduced Virtual Network Functions (VNFs). The VNF layer is based on building blocks in the VNF architecture. These blocks are a software implementation of network functions built on top of SDN. VNF can be connected or combined together like building blocks to offer a full-scale network communication service, this is also known as service chaining. For example, Virtualized Firewall Function for IP and Virtual Router.

3.4.3 Existing SDN Techniques

In the previous sections, the concepts of SDN and SDWN have been presented. In this section, we summarise five studies, which we believe are the most related to our proposed architecture. Specifically, these studies cover the use of SDWN in terms of network radio management, QoS awareness, QoE awareness, traffic management, data-aggregation and load balancing. In [73] the authors propose a framework in order to offer fair resources sharing. The idea is based on dividing the service into two classes, one for low data rate Stations (STAs) and the second for high data rate STAs. These classes were divided by using a slicing concept, with two OpenFlow switches connected through an SDN controller. The Slicing decision is based on latency, BW requirement and location. Simulation results show the proposed solution has the best result in terms of delay. However, this approach has a lack of user awareness and preferences, which has made this approach valid in specific simple scenarios only.

Similarly, work is presented in [74] where the author considers the QoE as a requirement, using specific flow parameters (Jitter, packet loss rate, and link BW). They propose a dynamic monitoring strategy so that the controller can manage to reassign a new IP address to the nodes once any problem is deduced' through the performance. This solution is promising the users a high QoE, but this solution relies on adaptive streaming which makes it difficult to measure the QoE, and that introduces a delay in the decisions making.

The author in [75] proposes flexible traffic management between providers' service and STAs. In addition, the author discusses the scalability in his proposal based on supporting multiple parallel sessions through a single OpenFlow gateway. The author was focusing only on the last mile connection between the providers and the gateway, deliberating the large-size network in regard to supporting multiple concurrent sessions through a single way. The only limitations in his proposal were that he didn't consider home networks and end-users as well, which can bring further flexibility performance. Thus, more work needs to be done at the end-users and home network.

In [76] the author proposes an architecture that extends the SDN and OpenFlow functionality, in order to support APs and STAs in a wireless network environment. In detail, the author adds some new commands, rules and actions in order to support resource allocation efficiency and a flexible routing scheme in mesh network. In his work he proposes a mesh router that consists of multiple virtual interfaces with a unique SSID to support OpenFlow data. Nonetheless, his solution was causing a delay through the HO process.

An architecture for load balancing based on SDN has been proposed in [77], using an OpenFlow switch and a centralised controller to allow real-time monitoring. Once the QoS of individual STAs starts degrading due to overburden at the APs, the monitoring tool will inform the controller, and the controller will relocate the STAs according to the available BW and the capacity of the APs. This solution was based on the available BW only and does not take into account other parameters such as delay or latency, and that results in a poor performance on the congested network. Table 3-2 summaries the existing architectures and compares them with other state-of-the-art methods in terms of OpenFlow, virtualisation and STAs awareness.

Table 3-2: SDN comparison

Architecture	Advantage	Enable Open Flow	Virtualis ation	STA involve ment	Disadvantage
Optimal Slice [73]	Slicing strategy based on the STAs requirement	Yes	YES	No	End users not considered (QoE)
QoE-aware [74]	QoE aware SDN-based video streaming protocol	No	No	No	complex algorithm which is causing delay in the decision
Traffic management [75]	Supporting multiple parallel sessions in Scalability network	Yes	No	No	uncompleted work at the end user and home network
SDWN [76]	flexible routing and data-aggregation,	Yes	No	Yes	HO Delay
OpenFlow Load [77]	Network management and load balancing	Yes	Yes	Yes	Poor performance on the congested network

The existing proposed architectures in the literature based on SDN provide promising performance. However, they are most suitable for specific scenarios. For instance, some of the architectures provide flexible traffic management only in the last mile connection and do not consider the access network. Other solutions focus on the load balancing for real-time monitoring between controller and OpenFlow switch. The load balancing is performed by relocating STAs to APs by observing the available BW only while not taking other parameters such as latency and jitter into the consideration which causes lack of QoS awareness. Therefore, it is essential to propose a solution that overcomes the limitations of existing architectures and assists in HO process and adds QoS and QoE requirements. This can be achieved by introducing intelligence in the centralised and scalable management of SDN networks, which is described in detail in the following sections.

3.5 Proposed Architecture Design

In this section, we present the design of the proposed SDWN architecture that will support our QoS and QoE-aware HO algorithms. The SDWN offers an extension of SDN to support flexible, fast and scalable management of the WLAN network. This architecture will enable the programmability to manage the data plan and HOs in unlicensed frequency. Specifically, a controller is considered for a WLAN network using the SDWN concept. Figure 3-6 shows the proposed architecture, including the controller, called the HO Management controller in the context of this project, and which implements HO algorithms based on FLCT.

The controller manages all the APs, thus facilitating the execution of the HO. Moreover, the centralised nature of SDWN enables the controller to obtain a global view of the network through monitoring and measurements, which will support the HO process.

3.5.1 The Control Layer

This layer consists of the controller, which is responsible for translating the application layer commands to the Infrastructure layer and also includes the monitoring manager, the Information Central Base (ICB) and HO manager. The main role of the monitoring manager is providing real-time monitoring to collect data from the managed APs and STAs such as bandwidth, Signal-to-Interference-plus-Noise Ratio (SINR), delay, and jitter. The ICB is responsible for storing the information collected by the monitoring tool. The HO manager uses such data to assist the wireless devices in the HO process, allowing them to always connect to the most suitable AP based on our algorithm. The monitoring information is sent to the application layer from the controller through the north-bound interface.

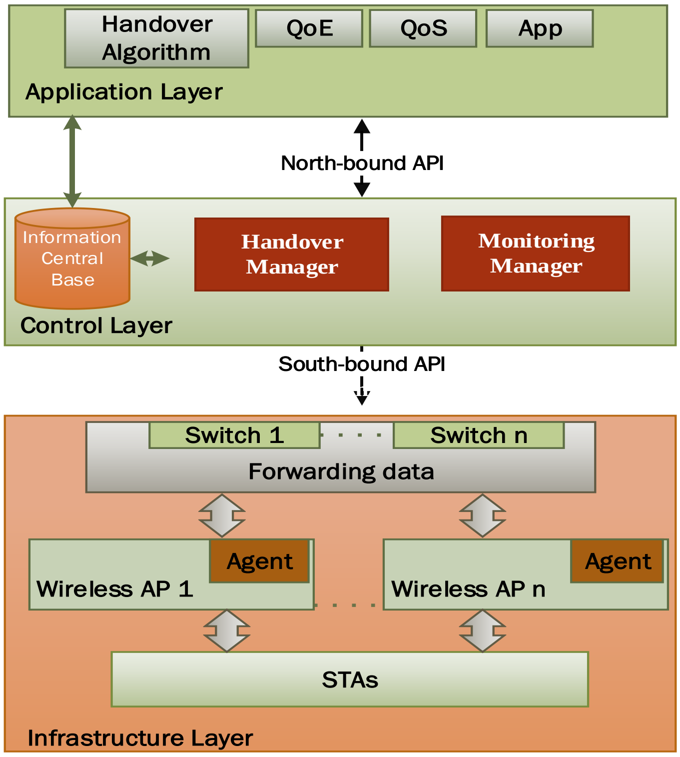

Figure 3-6: SDWN Architecture for QoE-Aware HO

3.5.2 Application Layer

This layer consists of all the applications built on the top of the SDWN. Such applications have the ability to access both lower layers (Control layer and Infrastructure layer) in order to manage the whole network functionalities. With the help of the information gathered through the controller, the applications abstract the network view and assist in the decision-making process. The proposed Handover algorithms are one example of these applications including the QoE Oriented Handover Algorithm, which is illustrated in chapter 4, the Optimised Handover Algorithm, which is illustrated in chapter 5, and finally, the priorities Based Handover Algorithm which is illustrated in chapter 6.

3.5.3 Infrastructure Layer

This layer consists of all the data plane elements such as APs, switches and STAs, and ruled by the controller to respond to orders such as the forwarding of packets, HO management, and wireless parameter tuning. Moreover, it provides control with live monitoring by constantly gathering network status. The infrastructure layer enables data forwarding and processing functionalities in the network such as processing of data paths. This is a physical layer which is monitored by the SDN controller through virtualisation.

3.5.4 North-bound API

A North-bound API is an application program interface that allows the components of the network to interact and communicate with a higher-level component through the controller. It defines the upward flow and is drawn at the top of the layer or component. The North-bound interface is regarded as output-oriented and often implemented in telecommunication and large-scale networks. The North-bound interface mostly uses protocols and languages such as Simple Network Management Protocol (SNMP) and Transaction Language 1 (TL1). The interface also provides support for higher level network management named as Operational Support System (OSS) by forwarding information related to alarm, performance, inventory, provisioning, configuration and security.

3.5.5 South-bound API

In contrast, a South-bound API allows the controller to interact and communicate with low-level components in the network. It has a direct connection with the lower component's North-bound interface. In the SDN paradigm, the South-bound interface enables communication between a controller, switches and the routers. So, the advantage of the South-bound interface is that it provides effective control over the network. The South-bound interface enables routers to send requests relayed from the North-bound interface and learn about the network topology. In this way, the SDN can modify network configurations according to the real-time requirements. OpenFlow and Cisco's OpenFlex interfaces are well-known examples of a South-bound interface.

3.5.6 Information Central Base

The Information Central Base (ICB) represents a central database which stores the information collected by the HO controller related to the network performance and user requirements. The main role of the ICB is to keep track of active flows that are currently connected to the network. In more detail, the ICB stores all the requirements in terms of QoS and the link capacity in terms of the available bit rate for the flows within the network [78].

3.5.7 Fuzzy Logic Control Theory

The Fuzzy Logic Control Theory (FLCT) is a functionality implemented in the application layer, which represents the main component of the HO strategy. This functionality is explained in detail in section 2.4.2.5 and we have implemented it in our approach for following reasons: 1) it has the capability of combining different attributes with multiple criteria and 2) it can handle imprecise data. FLCT consists of the membership function, membership degrees, and Fuzzy Handover Decision (FHOD). All these elements and their roles in the algorithms are described in the rest of this section.

First, the FLCT receives the real-time measurements as a set of parameters from the controller called membership values, which are the crisp values of bandwidth, Delay, Jitter and SINR. These values will be mapped between 0.0 (i.e., completely false) and 1.0 (i.e., completely true)

[39] in order to compute the so-called *membership function* for each parameter. Hence, it represents a set of values included between 0 and 1, which corresponds to a certain membership value. The *membership functions* of all the membership values represent the *membership degree* for a particular AP. While the *FHOD* represents a score used for each AP during the decision making and achieved through the *membership degrees*. All the details on the inclusion of these components in our FLCT-based algorithms will be provided in chapter 4.

3.6 HO Algorithm

The algorithm takes into account this set of parameters in order to enhance the overall QoE and QoS performance. All the STAs will be connected to the network and the controller will monitor the status of STAs and APs. Figure 3-7 shows the interaction of the FLCT algorithm with STAs and the Information Central Base.

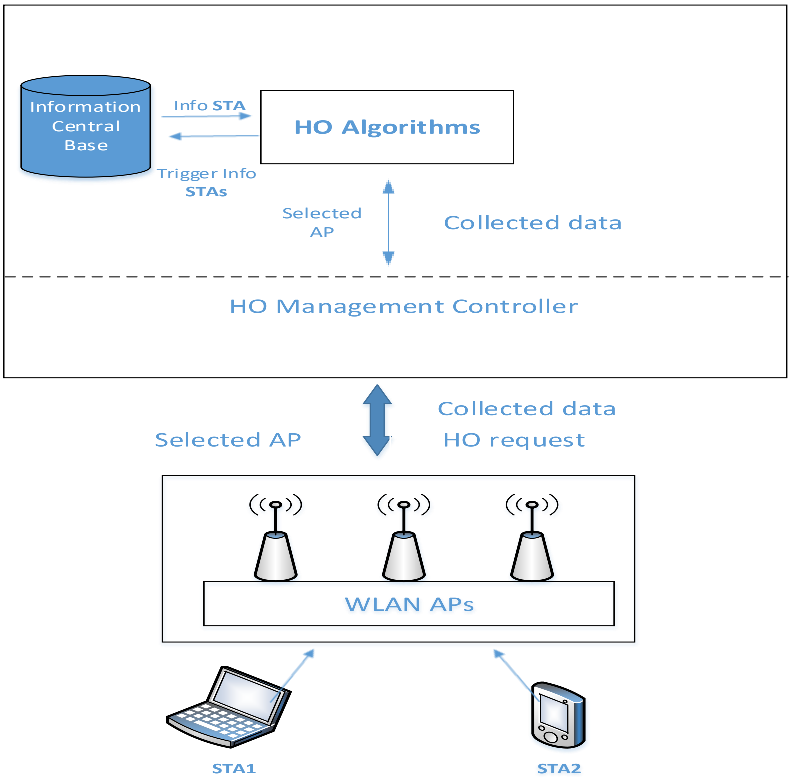

Figure 3-7: Interaction of FLCT algorithm with STAs and information central base

Figure 3-8 illustrates the messages exchanged among the entities included in the proposed architecture. The STAs will keep the system aware of the current status of their connection by measuring the experienced values of QoE and QoS, and send them periodically to the AP they are connected to (i.e., Current AP in the figure).

- This Current AP will send updated information to the controller regarding 1) the status of the STAs and 2) the information related to its current status, such as available bandwidth and number of connected STAs.
- The controller will evaluate the current state of the AP and if it meets the STA requirements or not. Specifically, if the current AP does not meet the requirements checked in the ICB, the controller will implement the FLCT rules, which will be explained in the next subsection, to select the optimal AP.
- The controller will send the decision through the *handover acknowledge switch message* illustrated in Figure 3-8 to the currently attached AP and the new APs called Target APs.
- The Current AP will send an acknowledge switch beacon to the STA and an HO confirmation message.
- The STA will send an association request to the targeted AP, which will repeat with an acceptance message as an HO confirmation.

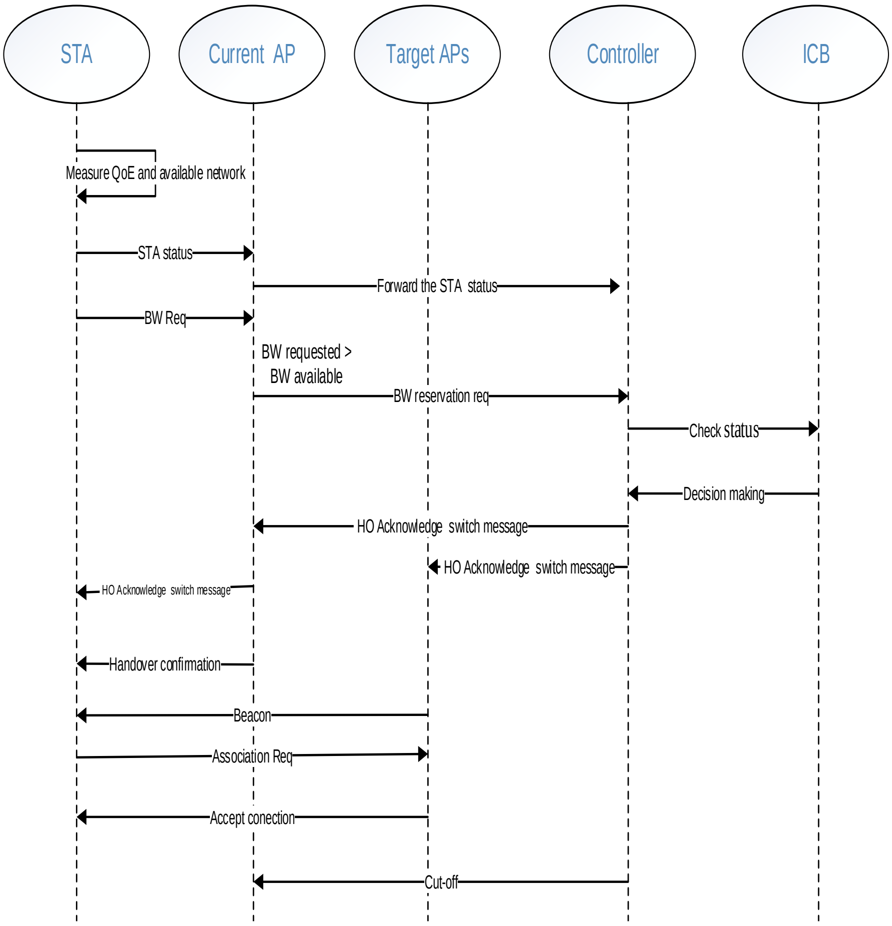

Figure 3-8: Signalling messages exchanged for the proposed Handover

3.7 Methodology

Based on our literature review and analysis, the proposed research methodology is based on the iterative and incremental approach illustrated in Figure 3-9 which divides the work into the 7 sections defined below:

- *Background and state of the art*: We have presented a review of the IEEE 802.11 standard evolution, SDN, its wireless version SDWN and all related technologies. Additionally, a survey of various approaches on the HOs mechanisms.
- *Analysis of the research problem and Identification*: In this section we summarised the problems and the limitations of the existing works.

- *Initial proposal*: In this section, we stated the novel contributions which will enhance HO processes.
- *Designing network architecture*: In this section we proposed the design of the networking architecture based on the proposed approach including the implementation of the algorithms.
- *Analytic modelling and implementation*: This section represents the implementation of the work and the analytical simulation results.
- *Result validation*: The collected results will be validated at this stage, which will also present feedback for necessary modification.
- *Improve the proposed work*: In this section the feedback from the validation results will be taken in order to enhance the performance by adding modification in order to improve the proposed work.

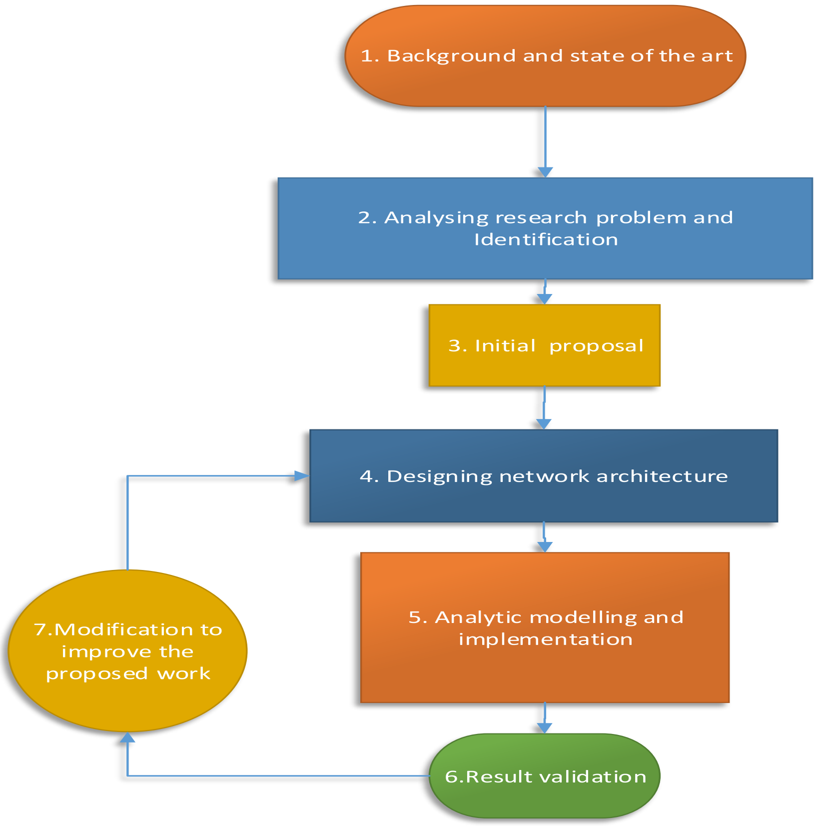

Figure 3-9: The proposed methodology

3.8 Summary

In this chapter, we have explained the limitations of mobility management in IEEE 802.11 along with current distributed and centralised network approaches, moreover, we have explained the need for a centralised network, and introduced SDN and SDWN as a promising model for the centralised approach. Background information of SDN and SDWN has been explained in the chapter, moreover, we have reviewed many studies and solutions based on SDN and SDWN. Also, in this chapter, we presented the proposed SDWN architecture that will support our QoS and QoE-aware HO algorithms. Finally, we introduced the proposed HO Algorithm based on FLCT. In the following chapter, we present the Quality of Experience Oriented Handover Algorithm.

Chapter 4 Quality of Experience Oriented Handover Algorithm

4.1 Introduction

This chapter presents our approach for a Quality of Experience Oriented Handover Algorithm in Wi-Fi environments. Existing HO methods do not meet the requirements of modern applications for mobile nodes due to the lack of awareness of the Quality of Service (QoS) and Quality of Experience (QoE) requirements of mobile users. Based on our proposed architecture in chapter 3, we introduce a Quality of Experience Oriented Handover Algorithm, which utilises Fuzzy Logic Control Theory (FLCT) at the application layer. This solution is based on the SDWN concept, where the Wi-Fi network is centrally controlled and the wireless Access Points (APs) are programmable. The proposed HO algorithm will assist wireless users to find the AP that can best support the application in terms of its QoS and QoE requirements and the use of FLCT provides promising performance results when compared to the 802.11 standards and another approach proposed in the literature.

4.2 Handover Strategy based on FLCT

In order to model the HO problem as FLCT, we need to first define the set of input parameters to be included. Specifically, the membership values considered in our HO strategy are SINR, bandwidth, jitter, and delay. As we will explain in subsection 4.3.2, a proper combination of these metrics will allow us to respect the use of QoE requirements during an HO.

4.2.1 FLCT Membership Functions

The first step toward the execution of the proposed FLCT-based HO strategy is the conversion of the membership values from their original format to the membership function. These conversions are explained in the rest of this subsection [79].

- **Membership Function for SINR:** is denoted μ_1, and calculated according to the following steps. First, the controller monitors and captures the $SINR$ values obtained by an STA through the following equation:

$$SINR = \Upsilon/(I + No) \qquad 4\text{-}1$$

Here Υ is the total amount of received signal power, I is the interference from other devices, and No is the total white noise.

Then, the membership function for $SINR$ is computed as below:

$$\mu_{1(\mathrm{x})} = \begin{cases} 0 & 0 \leq x \leq SR_{th} \\ \dfrac{SR_x - SR_{th}}{SR_{max} - SR_{th}} & SR_x > SR_{th} \end{cases} \qquad 4\text{-}2$$

Here SR_x represents the function of the $SINR_x$ at the AP, SR_{th} denotes the threshold of the $SINR$ level to be selected in each simulation, and SR_{max} denotes the maximum $SINR$ level that can be obtained by an STA. $\mu_{1(\mathrm{x})}$ for a certain selected SR_{th} is shown in Figure 4-1.

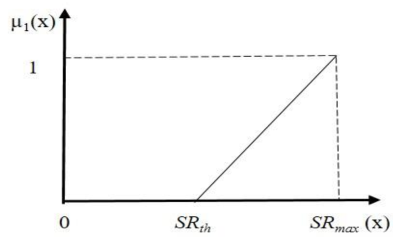

Figure 4-1: The membership function μ_1

- **Membership Function for Bandwidth:** is called μ_2, and is computed as follows:

$$\mu_{2(\mathrm{x})} = \begin{cases} \dfrac{B(x)}{B_{max}} & 0 \leq x \leq B_{max} \\ 0 & B(x) > B_{max} \end{cases} \qquad 4\text{-}3$$

Here $B(x)$ is the function of the amount of unused bandwidth, x, at the AP, and B_{max} denotes the maximum amount of bandwidth that the AP can provide. Figure 4-2 illustrates $\mu_{2(\mathrm{x})}$.

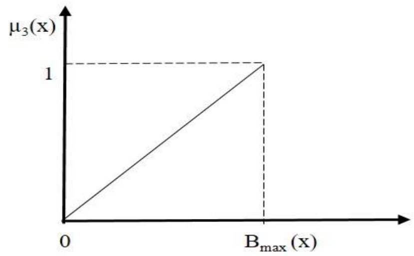

Figure 4-2: The membership function μ_2

- **Membership Function for Jitter:** is called μ_3 and denotes the function of the actual Jitter x at the AP. The membership function of the jitter is computed as follows:

$$\mu_{3(x)} = \begin{cases} 1 - \dfrac{J(x)}{J_{th}} & 0 \leq x \leq J_{th} \\ 0 & J(x) > J_{th} \end{cases} \qquad 4\text{-}4$$

Here $J(x)$ represents the function of the Jitter, and J_{th} is the threshold of the jitter to be selected in each scenario. An example of the membership function for the jitter for a certain value of J_{th} is shown in Figure 4-3.

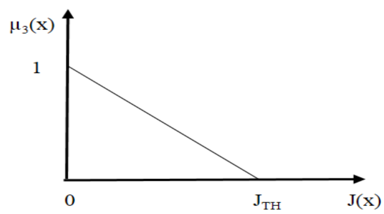

Figure 4-3: The membership function μ_3

- **Membership Function for Delay:** is called $\mu 4$ and is the function of the actual delay *x* at the AP. The membership function of the delay is defined as follows:

$$\mu_{4(x)} = \begin{cases} 1 - \dfrac{D(x)}{D_{th}} & 0 \leq x \leq D_{th} \\ 0 & D(x) > D_{th} \end{cases} \qquad 4\text{-}5$$

Here $D(x)$ represents the function of the Delay x and D_{th} is the threshold to be chosen in each case. An example of the membership function for the Delay and for a certain value of D_{th} is shown in Figure 4-4.

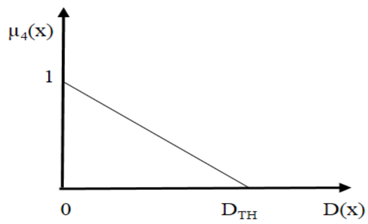

Figure 4-4: The membership function μ_4

4.2.2 FLCT Membership Degrees and FHOD

After the computation of the membership functions, we can calculate the membership degree. First, we consider *n* candidate APs for the HO execution and then we can define the membership degrees for all the APs illustrated in Table 4-1.

Table 4-1: Membership for all APs

	AP $_1$	AP $_2$	……	AP $_n$
SINR	$\mu_{1,1}$ (x)	$\mu_{1,2}$ (x)	……	$\mu_{1,n}$ (x)
BW	$\mu_{2,1}$ (x)	$\mu_{2,2}$ (x)	……	$\mu_{2,n}$ (x)
Jitter	$\mu_{3,1}$ (x)	$\mu_{3,2}$ (x)	……	$\mu_{3,n}$ (x)
Delay	$\mu_{4,1}$(x)	$\mu_{4,2}$ (x)	……	$\mu_{4,n}$ (x)

As such, element u_k illustrated in equation (4-6) includes all the membership functions for the generic AP_k (1 ≤ k ≤ n), that will form the basis in calculating the value of the membership degree forAP_k.

$$u_k = \begin{bmatrix} \mu_{1,k}(x) \\ \mu_{2,k}(x) \\ \mu_{3,k}(x) \\ \mu_{4,k}(x) \end{bmatrix} \tag{4-6}$$

Let us now define the weight vector *W* for the membership functions related to AP_k represented by the following equation:

$$W = (W_1, W_2, W_3, W_4) \tag{4-7}$$

Vector *W* can be rewritten as follows:

$$W = (w_1, w_2, w_3, w_4) = \left[\frac{\sigma_1}{\sum_{i=1}^{4}\sigma_i}, \frac{\sigma_2}{\sum_{i=1}^{4}\sigma_i}, \frac{\sigma_3}{\sum_{i=1}^{4}\sigma_i}, \frac{\sigma_4}{\sum_{i=1}^{4}\sigma_i}\right] \tag{4-8}$$

Where σ_i denotes the standard deviation of the membership function of parameter value *i*, which is defined through the following equation:

$$\sigma_i = \sqrt{\frac{1}{n-1}\sum_{k=1}^{n}[\mu_{i,k}(x) - \frac{1}{n}\sum_{k=1}^{n}\mu_{i,k}(x)]^2} \tag{4-9}$$

By using equations (4-6) and (4-7), we can define the FHOD for AP_k as below:

$$F_k(x) = Wu_k \tag{4-10}$$

This equation can also be rewritten as follows:

$$F_k(x) = w_1\mu_{1,k}(x) + w_2\mu_{2,k}(x) + w_3\mu_{3,k}(x) + w_4\mu_{4,k}(x) \tag{4-11}$$

Now we can define U as the membership degree matrix for the n APs denoted as follows:

$$U = \begin{bmatrix} \mu_{1,1}(x) & \mu_{1,2}(x) & \dots & \mu_{1,n}(x) \\ \mu_{2,1}(\mathrm{x}) & \mu_{2,2}(\mathrm{x}) & \dots & \mu_{2,\mathrm{n}}(\mathrm{x}) \\ \mu_{3,1}(\mathrm{x}) & \mu_{3,2}(\mathrm{x}) & \dots & \mu_{3,\mathrm{n}}(\mathrm{x}) \\ \mu_{4,1}(\mathrm{x}) & \mu_{4,1}(\mathrm{x}) & \dots & \mu_{4,1}(\mathrm{x}) \end{bmatrix} \tag{4-12}$$

Finally, from equations (4-7)-(4-12), we can obtain the following equation, which will allow us to define the FHOD values for each of the n APs:

$$F = WU \tag{4-13}$$

4.2.3 HO Algorithm based on FLCT

The FHOD values defined by eq. (4-13) will be considered to evaluate each AP during the execution of the FLCT-based algorithm. During the decision-making phase, the HO algorithm is executed by the controller to assign the best AP_k ($1 \leq k \leq n$) for a certain STA only if it can satisfy the following two conditions:

$$F_k(x) = \max\{F1(x), F2(x), \dots\ Fn(x)\} \quad \text{(a)}$$

$$F_k\ (x) - \ F_j(x) \geq \ F_{TH} \quad \text{(b)} \tag{4-14}$$

where, $Fj(x) = MaxF1(x), F2(x), \dots Fk - 1(x), Fk + 1(x), \dots., Fn(x)$. In detail, condition (a) is obtained by eq. (4-11), where the controller will select the highest value from the AP's candidate rank. Additionally, condition (b) will help to choose a candidate AP which is $\geq F_{TH}$ that is considered as a threshold for the FHOD. In our solution, F_{TH} is defined to guarantee a minimum value of Mean Opinion Score (MOS), indicated as MOS_{TH} (MOS threshold) and which will be defined based on the use case. The MOS is a metric usually considered as a tool to define the QoE and that provides the human user's view of the quality of the network [18]. Specifically, the MOS is an arithmetic mean of all the individual scores achieved by the result of subjective tests and can range from 1 to 5 which was illustrated previously in Table 2-4. The FHOD is evaluated using the MOS scores which will depend on our pre-defended rules as shown in Table 4-2. For instance, in the case when all the parameters scores high (H), the MOS will be considered as (H), when all the parameters scores medium (M) the MOS will be considered as (M), and when all parameters scores Low (L) the MOS will be considered (L). The rest of the mixed conditions are illustrated in the table below.

Table 4-2: QoE Rules

Rules Number	Jitter	BW	Delay	SINR	MOS
1	H	H	H	H	H
2	H	L	H	L	L
3	L	H	L	H	H
4	L	L	L	L	L
5	M	L	M	H	H
6	M	H	M	L	L
7	L	M	H	M	M
8	H	M	L	M	M
9	M	M	M	M	M

Focusing now on the algorithm implemented in the proposed architecture, each time that a generic STA *m* connected to the network experiences a MOS lower than MOS_{TH} due to another STA connecting to the same AP, the network triggers the algorithm. Hence, the HO management controller executes the FLCT-based algorithm to assign STA *m* to the AP satisfying conditions (a) and (b). Specifically, when the HO algorithm is triggered, the HO management controller computes the FHOD values by using equations (4-6)-(4-13) in the FLCT and for the set of candidate APs available for STA m retrieved from the ICB. Afterwards, the HO management controller will choose the best AP, i.e., the AP satisfying conditions (a) and (b).

4.3 Performance Evaluation

In this section, we illustrate the implementation of the proposed HO in the SDWN architecture in two scenarios. In the first scenario, we have used a simple wireless network, consisting of two APs and 5 STAs. The aim of this experiment is the validation of the algorithm. In the second scenario, we considered a more complex environment consisting of 4 APs and 25 STAs. This validates the algorithm in a dense scenario and moreover, includes a comparison against a solution found in the state of the art [80]. In general, the implementation of both scenarios is divided into the following three processes:

1. **Monitoring and information gathering process.** This module gathers all the information requirements from the STAs and APs that will allow it to compute the membership values (bandwidth, SINR, delay and jitter). Note that all this information will be stored in the ICB and updated every time a new STA joins the network.
2. **Weight vector and membership degree process.** Every time the execution of the HO is triggered for a connection of a new STA, the controller will determine an FHOD value for each candidate AP by calculating the weight vector and membership degree for all the membership values according to equations (4-6)-(4-13).
3. **Fuzzy Decision-Best Selection process**. This module executes the HO using FLCT which selects the AP that guarantees the conditions dictated by equations (4-14).

4.3.1 Evaluation of the FLCT-based HO in a simple wireless network.

The proposed SDWN-based architecture, which implements the FLCT-based HO, has been designed and assessed using OPNET, according to the scenario described in Figure 4-5, we consider a WLAN consisting of two APs managed by an SDWN controller and five STAs that need an AP allocation.

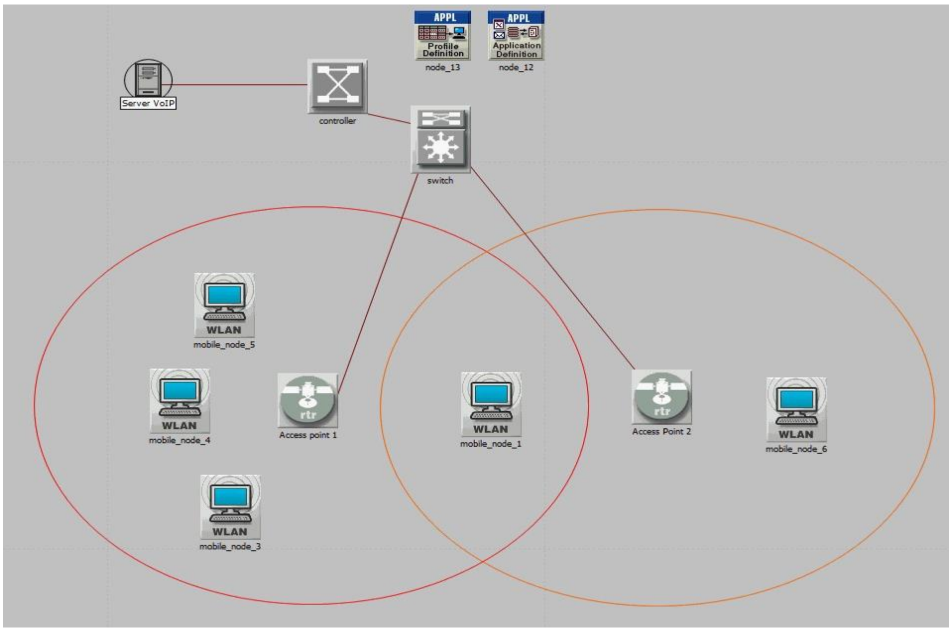

Figure 4-5: Simulated Simple Scenario-based on the SDWN

The WLAN simulated in this scenario is based on IEEE 802.11g which offers a maximum bandwidth of 54Mbps as a standard. However, in order to demonstrate the effectiveness of the proposed algorithm, we assume that the network is also serving other devices and that the capacity available to the STAs is limited to 1Mbps, in order to demonstrate and evaluate the algorithm performance in the congested network. We assume that STAs are running Voice over IP (VoIP) applications which have the traffic characteristics in Table 4-3.

Table 4-3: Traffic Characteristics

Characteristic	Value
VoIP encoder	G711
Voice frames per Packet	1
Type of service	Best Effort (0)
Bit rate (kbps)	64
Voice Frames per Packet	1

As illustrated in Figure 4-5, in the simulated scenario, STA1 is located in an area of overlap between the two APs. STA1 is initially associated with AP1 together with other STAs (i.e. STA2, STA3 and STA4 in the Figure). During the simulation, and after approximately 100 seconds, STA1 establishes a VoIP call and, then after 5 minutes STA2, STA3 and STA4 also establish a VoIP call via the same AP. The value of MOS_{TH} for this experiment is set to 3.1. We have chosen 3.1 MOS to guarantee the minimum requirements for the fair/slightly annoying service which is described previously in Table 2-4. For instance, when the service decreased below the 3.1 MOS, the user will experience bed connection due to the high jitter, dropped packets or the delay. Therefore the minimum requirements in our simulation is 3.1 MOS. During the first 5 minutes, therefore, STA1 maintains its connection with AP1, as it experiences MOS greater than MOS_{TH}. However, once nodes STA2, STA3, and STA4 start establishing VoIP connections, STA1 experiences a decrease of its MOS to a value below the threshold. Therefore, the controller executes the FLCT-based algorithm to discover a better service from a neighbouring AP, in this case, AP2. Through the information received by the STAs and the data stored in the ICB, the controller will execute the FLCT-based algorithm described in the previous sections, connecting STA1 to AP2 based on the results achieved (4-14) through Eq.(4-15).

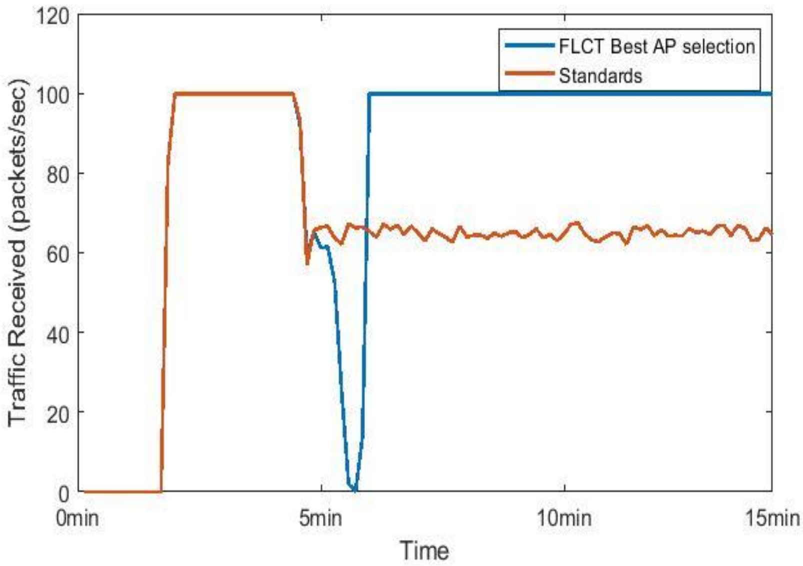

Figure 4-6: STA1 traffic as a function of time

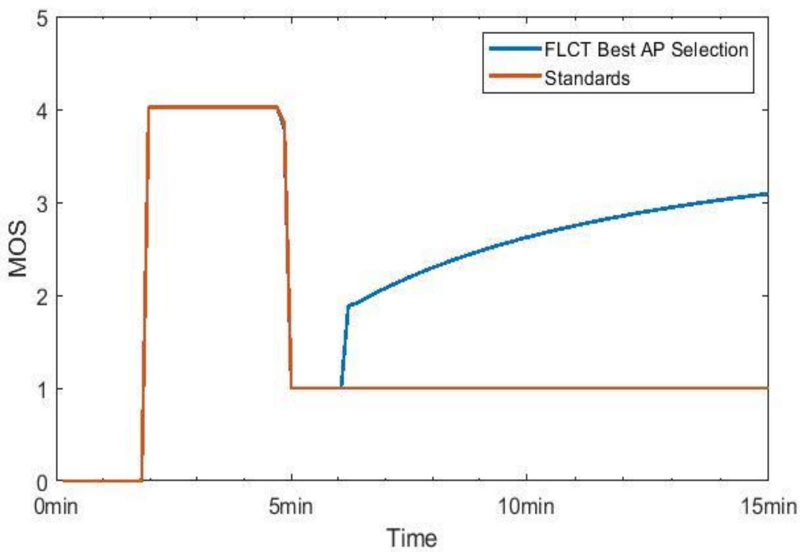

Figure 4-7: STA1 MOS value as a function of time

Figure 4-6 and Figure 4-7 present the performance results of STA1 in terms of received traffic (i.e., packets received per second) and MOS as functions of the simulation time. Both figures show the temporal evolution of the performance results during 15 minutes. In order to demonstrate the effectiveness of the algorithm, we compare it with IEEE standard 802.11g which is represented by the orange line in the figure. The IEEE standard 802.11g depends on the RSS only, while our proposed solutions depend on QoE, which is represented by the four parameters SINR, Delay, BW and Jitter. For instance, the QoE value will depend on the variation of the four parameters values as we have explained it in Table 4-2 previously. These results demonstrate the improvement achieved in terms of received traffic and MOS for STA1 through the proposed algorithm and how it overcomes the IEEE standard in a simple network scenario. In the next section, we will demonstrate the proposed solution in a more complex scenario.

4.3.2 Evaluation of the FLCT-based HO in a complex wireless network

Another experiment has been done to the proposed SDWN-based architecture in order to demonstrate the performance of the algorithm for the overall network. In this scenario, we implemented a complex wireless network which includes 4 APs and 25 STAs running two different types of applications during 15 minutes. In total, 12 STAs will run VoIP while 13 STA will run Video. As is described in Figure 4-8, we considered a WLAN consisting of 4 APs managed by the HO management controller and 25 STAs that need an AP allocation. Through the simulation, 2 STAs (1-1 and 1-19) are located in the overlapped area. After 100 seconds, those STAs establish a VoIP call and video conferencing application, then after approximately 4 minutes the rest of the STAs establish a VoIP call and video conferencing application. The value of MOS_{TH} for this experiment is set to 3.1. As we have stated above, we simulated only 25 SATs to demonstrate the proposed algorithm. In order to trigger the HO algorithm, we assume that each AP capacity is limited to 2Mbps. In that case, the 25 users will cause a congested network (bottleneck) where the controller will be able to activate the HO algorithm and reallocate the users to the best possible service.

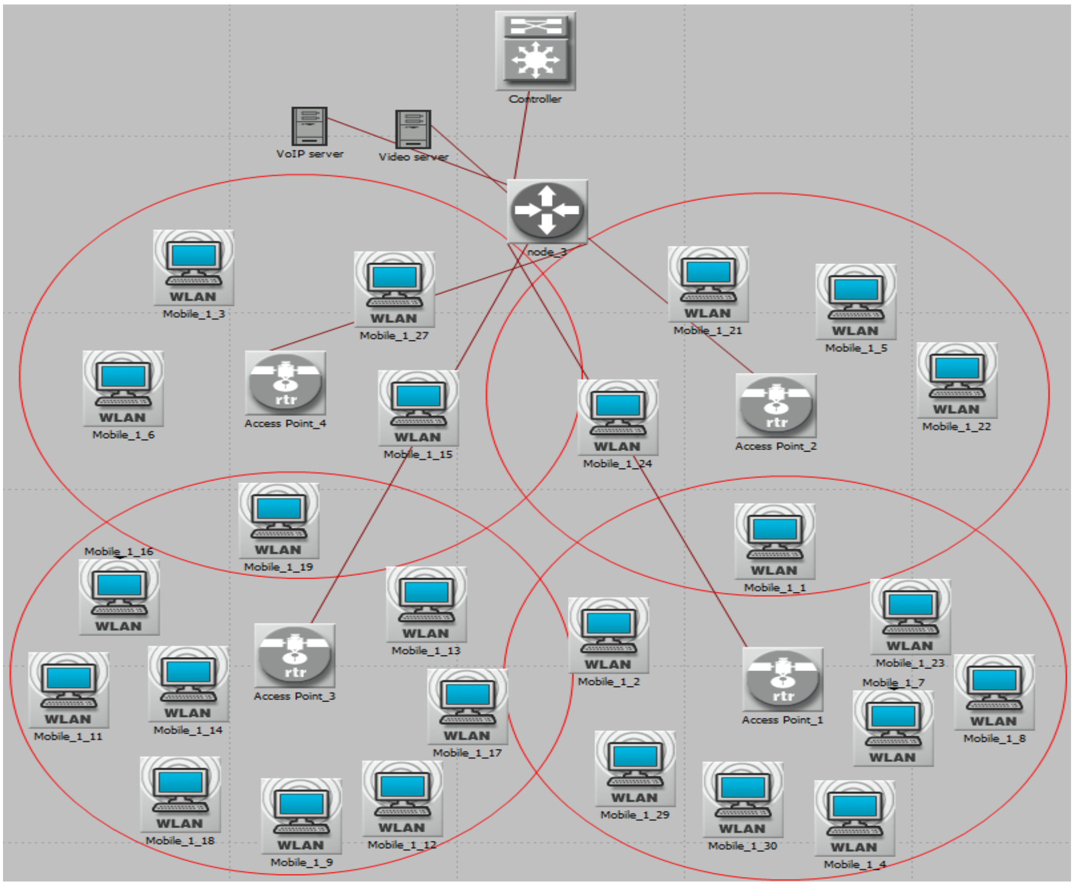

Figure 4-8: Simulated Scenario based on the SDWN

We assume two different types of applications running in the STAs, Voice over IP (VoIP) and Video Streaming, which have the traffic characteristics in terms of codec, bit rate, resolution, and corresponding achievable MOSs illustrated in Table 4-4.

Table 4-4: Traffic Characteristics

Application	codec	Bitrate (kbps)	Resolution (pixels)	MOS
VoIP	G7.11	64	----------	4.0
Video	H.264	438	525*384	4.0

As illustrated in Figure 4-8, STA1 and STA19 are located in areas of overlap among APs and are initially associated with AP1 and AP4, respectively. During the simulation, after approximately 100 seconds, STA1 and STA19 both establish a VoIP call and then, after 5 minutes, the rest of the STAs connected to the same APs as STA1 and STA19 and establish VoIP calls and Video streaming applications. As will be explained in the next subsection, these new session establishments will trigger the proposed algorithm. In order not to downgrade the MOS below a fair value, we have chosen MOS_{TH} in condition (b) equal to 3.1, which corresponds approximately to 39.68 kbps in terms of VoIP and to 271.5 kbps in terms of video.

Moreover, to benchmark the performance of our proposed HO algorithm, we compare it against the following reference strategies: 1) a case in which an HO is not executed at all as foreseen in the 802.11 standards; and 2) the HO algorithm proposed in [81], which fairly distributes the STAs in the network based on the AP load and RSSI, and is called Load-RSSI-based in the next section.

4.3.3 Performance Results

During the first 5 minutes, STA1 and STA19 maintain their connection with their current APs experiencing a MOS greater than MOS_{TH}. After the rest of the nodes start establishing VoIP and video streaming connections in AP1 and AP4, STA1 and STA19 start experiencing a decrease of their MOSs until they reach a value below the threshold. Therefore, the controller executes the FLCT-based algorithm to discover and assign a better AP, in this case, AP2 for STA1 and AP3 for STA19.

Figure 4-9 presents the performance results of our algorithm against the state of the art for STA1 and STA19 in terms of their average throughput (i.e., bits received per second), and Figure 4-10 presents MOS as functions of the simulation time. Both figures show the temporal evolution of the performance results during 10 minutes. These results demonstrate the improvements achieved in terms of throughput and MOS for STA1 and STA19 through the proposed algorithm.

Specifically, from Figure 4-9, we can observe that our algorithm outperforms the 802.11-based strategy (called standard here), and the Load-RSSI-based solution in terms of throughput. For instance, at the end of the simulation, the average throughput experienced by both STA1 and STA19 is around 40Kbits for our algorithm, while it is around 32Kbits and 27Kbits for the Load-RSSI based and 802.11-based solution, respectively. Additionally, from Figure 4-10 we can observe that our proposed approach outperforms the 802.11-based and the Load-RSSI based solutions also in terms of MOS. For instance, at the end of the simulation, the MOS is 2.5 for our algorithm, while it is 1.5 for the Load-RSSI-based solution and 1 for the 802.11-based one.

Finally, the result of the accumulated throughput experienced by all the STAs connected to the network is presented in Figure 4-11. This figure shows a gain of approximately 17% and 8% in terms of the accumulated throughput for the overall network achieved by applying our algorithm compared to the 802.11-based and the Load-RSSI-based solution, respectively. The gain was a result of our proposed algorithm that is able to identify STAs below the threshold and relocate them to the best candidate AP.

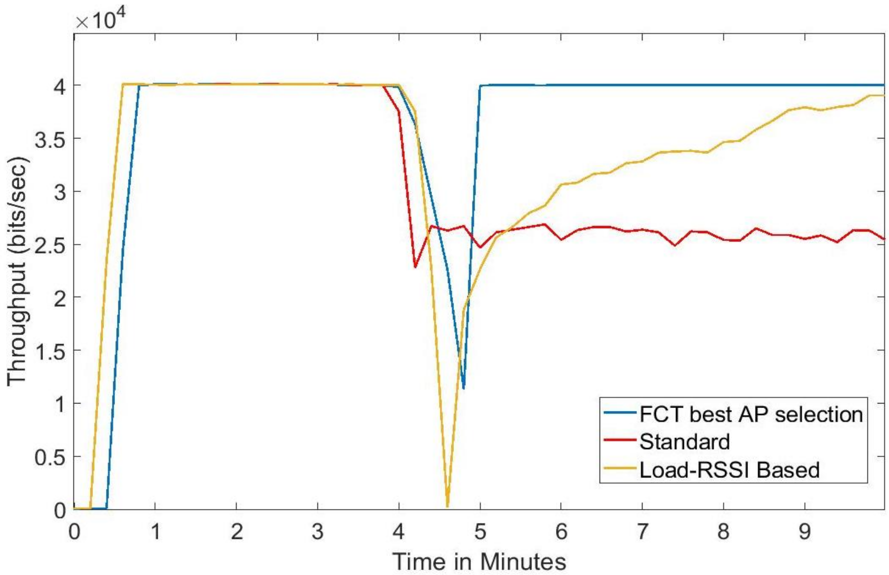

Figure 4-9: STA1 and STA19 traffic received as a function of time

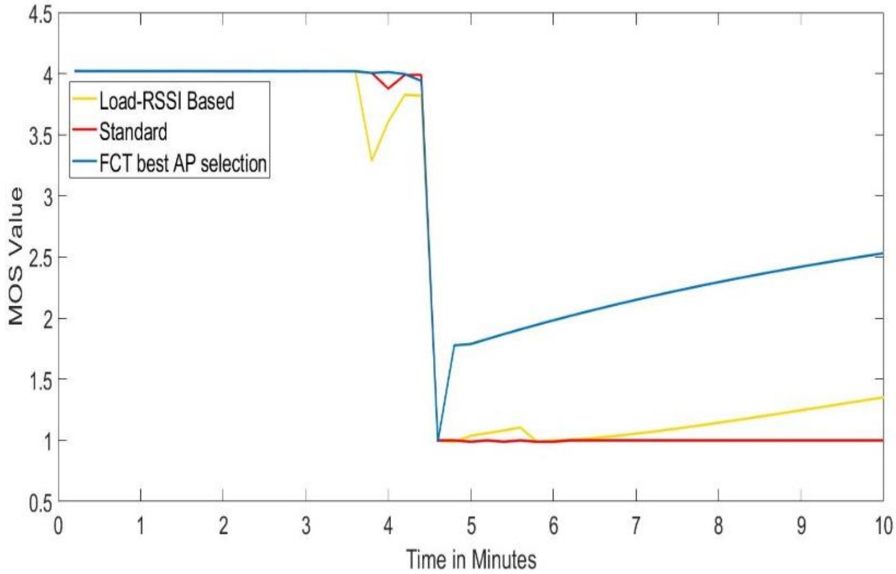

Figure 4-10: STA1 and STA19 MOS value as a function of time

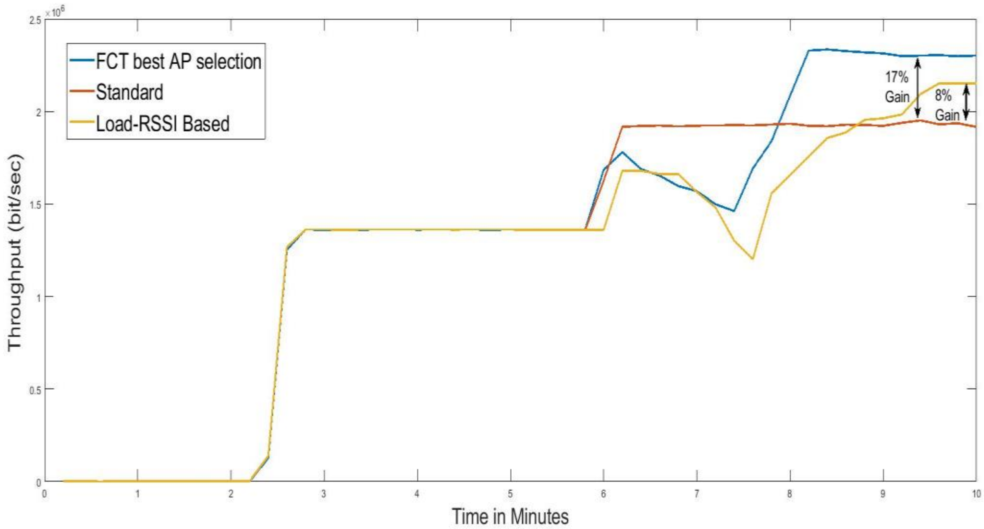

Figure 4-11: Accumulated throughput experienced by all the STAs

4.3.4 Limitation of the QoE-Oriented Approach

The proposed approach provides good performance in terms of QoS and QoE in a small-scale network which is not highly dense. However, in large scale networks due to increased density, it is observed that the nodes start disconnecting and reconnecting in a short period of time causing a ping-pong effect which we explained early in section (2.4.2.1). The ping-pong effect degrades the performance and reduces the QoS and QoE received by the end STAs because it costs lots of unnecessary overhead messages. Therefore, in the following chapter, we propose an improved HO algorithm which reduces the ping-pong effect by using Adaptive Hysteresis Values (AHV).

4.4 Summary

In this chapter, we presented a Quality of Experience Oriented Handover Algorithm for Wi-Fi environments, which supports seamless HO considering the user's QoS and QoE requirements. The proposed solution implements an algorithm at the application layer based on Fuzzy Logic Control Theory (FLCT) that considers the QoE of the users in order to ensure the best AP connection. Moreover, an assessment has been done compared to the existing 802.11 standard and another approach presented in the literature in order to highlight the effectiveness of the proposed algorithm in terms of throughput. For instance, our simulation campaign has successfully demonstrated that the proposed FLCT-based HO algorithm improves on the standard by a gain of 17% and the other algorithm by a gain of 8%. However, though the FLCT algorithm provides better performance, we observed this algorithm does not scale well to larger networks. Consequently, the high density of APs and STAs causes redundant or ping-pong HO. Therefore, in the following chapter, we propose an Optimised handover algorithm for dense WLANs which utilises Adaptive Hysteresis values with FLCT to reduce redundancy and ping-pong HO effect.

Chapter 5 Optimised Handover Algorithm for Dense WLAN Environments

5.1 Introduction

This chapter presents an Optimised Handover Algorithm for Dense WLAN Environments which improves the previous version based on FLCT and is designed to be effective in large network environments with a high density of APs and STAs, which increases the chances of the Ping-Pong HO effect.

We, therefore, extend the proposed SDWN architecture with an optimised handover algorithm that considers QoE and QoS by applying an optimised HO algorithm for Wi-Fi networks based on Fuzzy Logic Control Theory (FLCT) and Adaptive Hysteresis values (AHV). Through SDWN, networks are monitored and controlled centrally and the virtual Access Points (APs) are programmable. The proposed HO algorithm solution will guarantee the best possible connectivity to the users in terms of their QoE and QoS requirements. The use of FLCT, which in our solution includes QoS, QoE and AHV dynamic values in the HO algorithm, shows promising performance results by selecting the best candidate AP, reducing the redundant HO, and reduces the messaging overhead.

5.2 Enormously Dense Wireless Networks

High-density wireless networks are areas that provide service to hundreds or even thousands of wireless devices in a limited area. For instance, high density wireless indoor and outdoor networks include stadiums, airports and train stations, exhibition halls, shopping malls and e-learning environments like universities. These networks differ in their common characteristics such as the type of network, the applications, traffic conditions and usage. For example, in e-learning networks, the APs are installed in classrooms and the corridors; the teachers and students (STAs) use services such as streaming video for demonstrations, file transfer and sharing, and downloading software applications. The provision of wireless services in these places present a number of challenges during the design process of wireless networks. These challenges are related to the total anticipated number of wireless devices connected to the network, separation between devices and the mobility of users. The increasing demand for wireless users in these networks is limiting the capabilities of current wireless technologies and causing an excess of HOs and the ping-pong HO effect. Airports are a good example of dense networks due to many factors, such as a high number of APs installed by the service providers and also a high number of passengers connecting to WLANs. Another factor is the needs of the high capacity in terms of BW; in fact, according to Laurent in [82], 50% of the passengers use Video High Definition (VHD) which requires a high BW of approximately 100Mbps. Add to that, many passengers use online gaming, virtual private networks (VPNs) that require only low latency, and BW of approximately 20Mbps. Another negative factor in dense networks is the distribution of the APs as the distance between them can cause interference, which results in a performance decrease of the provided services. All those factors could result in the degradation of user QoS/QoE, especially in the case of real-time applications, which can require numerous seamless HOs. Figure 5-1 illustrates an example of signal strengths captured in a dense residential area, which represents another typical example of these environments. In this figure, we have used the Wi-Fi analyser app called NetSpot, which is installed in Android devices to measure the local Wi-Fi environment. From the figure it is clear how the 2.4 GHz bandwidth is densely populated in this area, creating massive potential interference, which can cause performance degradation and the consequent undesirable redundant HO. Therefore, the introduction of the Optimised Handover Algorithm for Dense WLAN Environments will enhance the network performance in terms of unnecessary HO by taking into account both QoS and QoE requirements and the use of AHV.

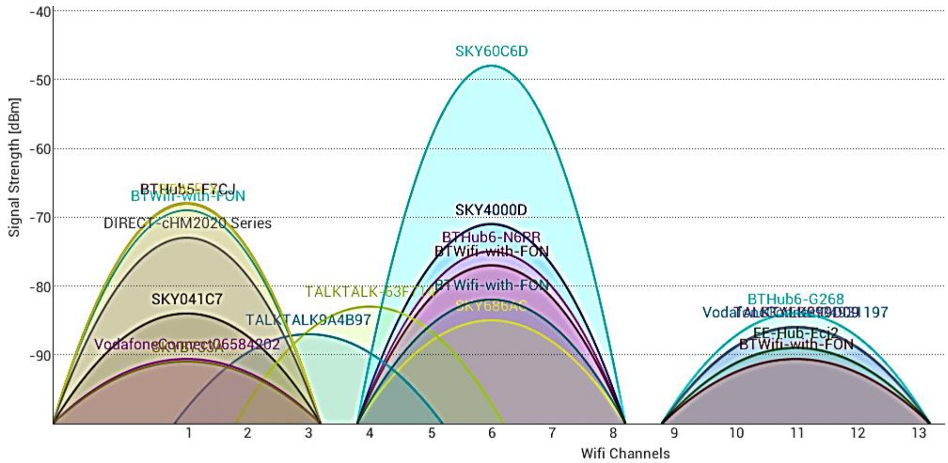

Figure 5-1: Example of signal strengths captured in a residential area

5.3 Adaptive Hysteresis Values

As we have mentioned in the previous section, redundant HOs become challenging especially in a dense network environment, such as campuses, airports and business centres. Therefore, new techniques are needed in order to optimise the handover decisions. In [83] we have presented an HO technique based only on QoE, which is efficient in small network areas. Therefore, we now introduce a new element in our HO approach in order to reach the most optimal HO decision through the AHV values at the edge of QoE levels.

The QoE level at the current or candidate APs is included in a range of different values because of the movement of the STAs, or the nature of the currently running application. For this reason, we introduce the Adaptive Hysteresis Value (AHV). AHV is the margin provided for maintaining the minimum difference between the QoE received from the current AP and the target AP. It is calculated in real-time, associated with the difference between the minimum and maximum QoE in an overlapped area and is derived as follows [84]:

$$AHV = max\{AHV_{max} \times (1 - 10^{\frac{QoE_{act} - QoE_{min}}{QoE_{min} - QoE_{max}}})^{exp}; AHV_{min}\} \qquad (5\text{-}1)$$

Where QoE_{act} is the actual QoE at the STA which is ranging from 1 to 4 MOS, QoE_{max} and QoE_{min} are maximum and minimum QoE values, respectively, which could be offered by the APs in the overlapped area. The value of the exponent (exp) is equal to 4 and AHV_{min} is the minimum AHV that can be set up equal to 0. The parameters exp and AHV_{min} can influence the performance of the AHV adaptation. However, the investigation of the optimal setting of both parameters is out scope for this thesis. Therefore, we have chosen the values according to the authors in [84][85].

The minimum and maximum QoE values also must be measured for the utilisation of the AHV. QoE_{min} refers to the AP that could offer a minimum QoE level, where the STA is able to receive the service between fair and poor, which is no less than 2.5 in terms of the Mean Opinion Score (MOS). The QoE_{max} refers to the highest value of QoE that the candidate AP could offer, and this can be determined by using Eq. (4-6)-(4-13). The role of the AHV in the Optimised AP Selection algorithm will be provided in Section 5.4.

5.4 Optimised AP Selection

The FHOD values defined through Eq. (4-13) will still be considered to evaluate each AP during the execution of the Optimised AP Selection algorithm and the $AHVs$ defined by Eq. (5-1). In detail, the AHV will be evaluated for each individual STA and then added as an Adaptive offset value in the decision-making phase, as defined in condition (c) in Eq.(5-2). Then, the HO algorithm is executed by the controller to assign the best AP_k for a certain STA only if it can satisfy the following conditions:

$$F_k(x) = \max\{F1(x), F2(x), \dots Fn(x)\} \qquad \text{(a)}$$

$$F_k\,(x) - Fj(x) \geq F_{TH} \qquad \text{(b)} \qquad \text{(5-2)}$$

$$F_k > F_c + AHV \qquad \text{(c)}$$

where, $Fj(x) = MaxF1(x), F2(x), \dots Fk-1(x), Fk+1(x), \dots., Fn(x)$and, F_c is the current connected AP.

In Eq.(5-2), the condition (a) is obtained by Eq. (4-11) and allows the controller to select the highest value from the APs candidates' ranks. While condition (b) ensures that the candidates AP is $\geq F_{TH}$. Finally, the condition (c) is obtained by Eq.(5-1) and allows the controller to calculate the AHV, which avoids redundant HOs by adding the adaptive offset value for each individual STA. Finally, F_{TH} represents the minimum guaranteed value of MOS.

Focusing now on the algorithm implemented in the proposed architecture, each time that a generic STA m connected to the network experiences a MOS lower than F_{TH}, called MOS_{TH} from now on, due to another STA connecting to the same AP, the network triggers the algorithm. Therefore, the HO management controller executes the Optimised AP Selection algorithm to assign to STA m to the AP satisfying conditions (a), (b) and (c). In detail, when the HO algorithm is triggered, the HO management controller first calculates the FHOD values by using equations (4-6)-(4-13) in the FLCT and for the set of candidate APs available for the STA achieved from the ICB. Afterwards, the HO management controller will select for STA m the best AP satisfying conditions (a), (b) and the final condition (c), which is responsible for avoiding the ping-pong effect.

5.5 Performance Evaluation

5.5.1 Simulated Scenario

Figure 5-2 illustrates the scenario implemented using OPNET to assess the proposed SDWN-based architecture, which provides HO functionality based on our Optimised AP Selection. In detail, the WLAN is again based on IEEE 802.11g which offers a maximum bandwidth of 54Mbps as a standard and consists of 25 APs controlled by the Handover management controller and 250 STAs that need an AP connection. The simulation configuration parameters are illustrated in Table 5-1 below [86].

Table 5-1: Simulations parameters

Parameters	Value
AP coverage area	Circular with one cell, R = 25 meters
Overall AP coverage area	500x500
Number of APs	25
Number of STAs	250
MAC Type	802.11g
Transmit Power	0.005 Watts
Reception Power threshold	-95 dBm
AP beacon interval	0.02sec

We Define the received power threshold (receiver sensitivity) value of the radio receiver as -95 dBm for arriving WLAN packets. Packets with a power less than the threshold are not sensed and decoded by the receiver. Hence, such packets don't change the receiver's status to busy and they are not detected by the WLAN MAC through its physical sensing mechanism.

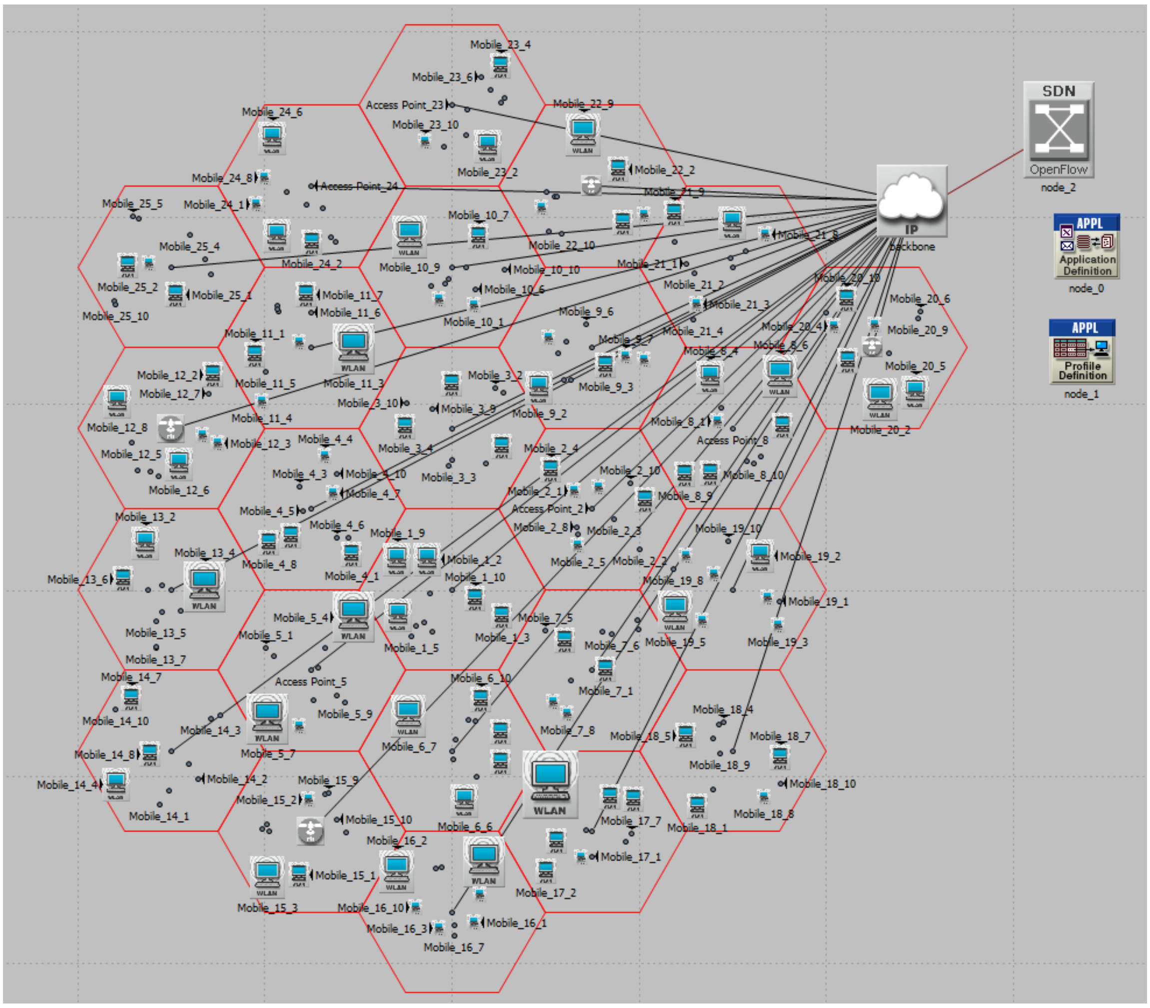

Figure 5-2: Simulated Scenario based on the SDWN

We again assume two types of applications are running in the STAs, i.e., Voice over IP (VoIP) and Video Streaming. The traffic characteristics in terms of codec, bit rate, resolution, and corresponding achievable MOS shown in Table 5-2.

Table 5-2: Traffic Characteristics

Application	codec	Bit rate (kbps)	Resolution (pixels)	Ideal MOS
VoIP	G7.11	64		4.0
Video	H.264	438	525*384	4.0

As illustrated in Figure 5-2**,** in the simulated scenario each cell has an AP located in the middle. Once the simulation starts, each of the 250 STAs is created every 5 to 10 seconds, running

VoIP or Video applications. STAs have been distributed randomly and uniformly in the 25 cells covered by the APs, as will be described in the following subsection, these new session establishments trigger the proposed solution. We have chosen MOS_{TH} threshold in condition (b) equal to 3.1, in order not to decrease the MOS below a fair value, which for instance corresponds approximately to 271.5 kbps in terms of video, and 39.68 kbps in terms of VoIP. Moreover, to benchmark the performance of our proposed HO algorithm, we compare it with our previous work based on FLCT [83]. Note that our previous algorithm based on FLCT provided improvements over the IEEE 802.11 standards and the state of the art such as the work presented in [83].

5.5.2 Simulation Results

As previously stated, the STAs have been created uniformly every 5 to 10 seconds in random locations. Then, after approximately 130 to 150 STAs have joined the network, the algorithm was triggered when the volume of new connections caused a sufficient reduction of the MOS below the predefined threshold for certain STAs. Once the MOSs of the affected STAs reached a value below the threshold, the controller executes the HO algorithm to discover and assign a better AP for such STAs.

Figure 5-3 and Figure 5-4 present the performance results of our Optimised AP Selection algorithm against the FLCT-based one in terms of MOS and average throughput at the STAs (i.e., bits received per second), as functions of the number of STAs. Both figures show the temporal evolution of the performance results from the first STA joining the network, until the last one. These results demonstrate the improvements achieved in terms of throughput and MOS for the overall network through the proposed algorithm.

Specifically, from Figure 5-3, we can observe that our proposed approach outperforms the FLCT-based one in terms of MOS. For instance, at the end of the simulation, the MOS is 2.5 for our algorithm, while it is 1.8 for the FLCT -based one. The proposed algorithm maintains to keep the users above the 3.1 MOS. However, the network will be over-congested just after approximately 140 flows joined, therefore, the MOS will keep decreasing with the increase of the flows.

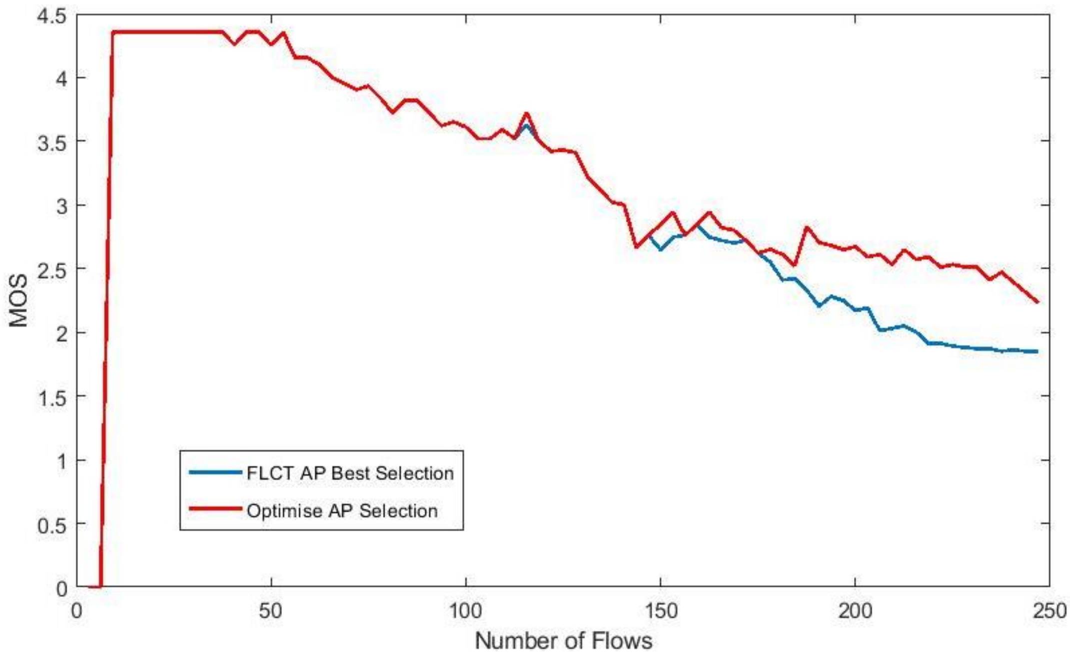

Figure 5-3: Overall MOS value as a function of number of flows.

In Figure 5-4, we can observe that our algorithm outperforms the FLCT-based one also in terms of average throughput (i.e., bits received per second) received at the STAs. For instance, at the end of the simulation, the overall network throughput experienced is around $2.3\text{x}10^4$ Kbits for our algorithm, while it is around $1.5\text{x}10^4$ Kbits for an FLCT-based solution.

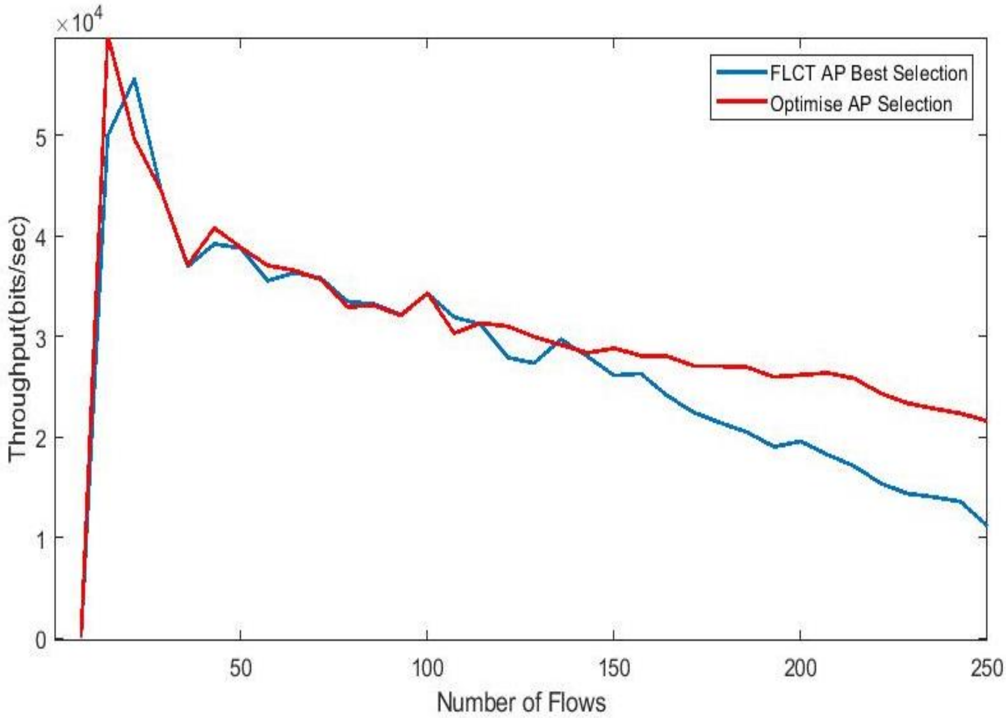

Figure 5-4: Average throughput received at STAs

In Figure 5-5, we present the result in terms of the end-to-end delay. This figure illustrates a gain of roughly 25% in terms of the end-to-end delay achieved by applying our proposed solution compared to the FLCT-based approach.

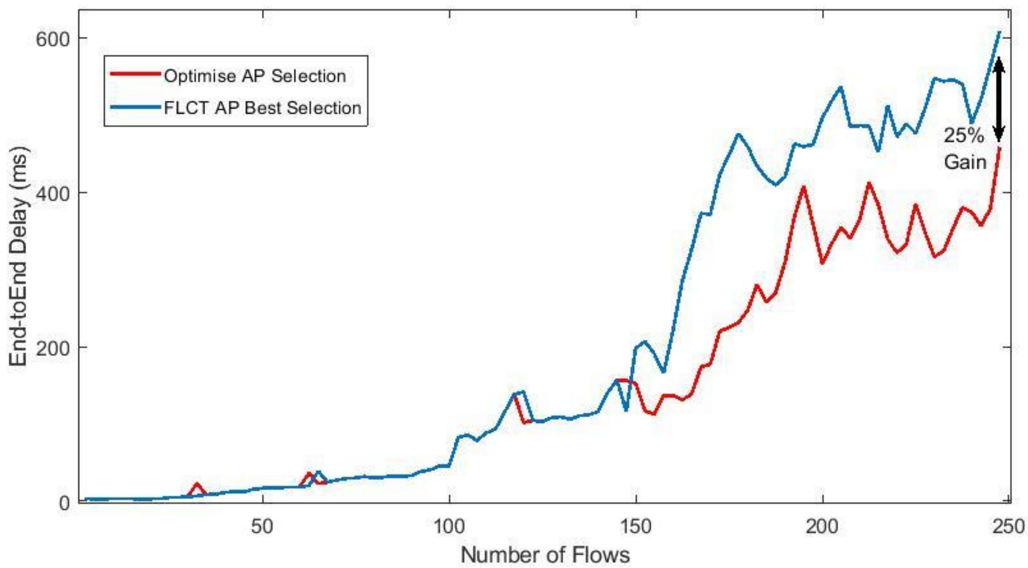

Figure 5-5: End-to-End Delay

Finally, Figure 5-6 illustrates the overall numbers of HO and the Number of handovers per application (VoIP and Video). We can observe that our algorithm reduces the HO by around 20% compared with FLCT Best AP Selection. The gain of that is reducing the overhead messages which consume about 20% from the overall throughput according to [87].

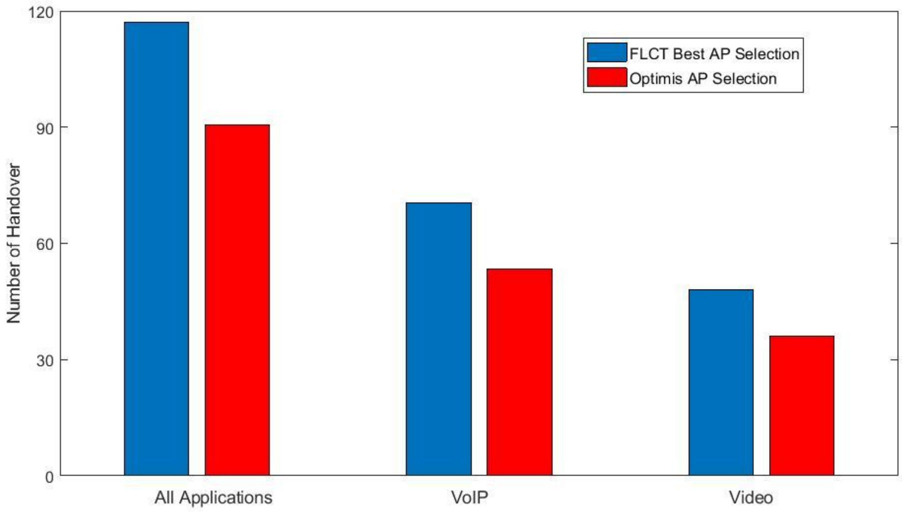

Figure 5-6: Overall numbers of HO

From the results illustrated in the figures above, we can see that our new algorithm outperforms the FLCT-based HO considered in the previous chapter in terms of overall MOS, average throughput received and End-to-End delay. However, this approach still cannot ensure a good service for all or part of the users, due to over-congestion of the network. Therefore, in the following chapter, we will present a further extension of the algorithm, which will overcome this problem providing the users characterised with high priority with a guaranteed service.

5.6 Summary

In this chapter, we proposed an optimised handover algorithm based on SDWN, considering the user's Quality of Experience (QoE) requirements, based on FLCT and AHVs. This algorithm performs well in dense WLAN environments. In detail, this solution implements an algorithm that considers the QoE of the users in order to ensure the best AP connection and specifically adopts the AHV to avoid unnecessary ping-pong handovers. Moreover, we compared the results with our FLCT-based approach, demonstrating how the new version outperforms it and therefore also the IEEE 802.11standards. The proposed algorithm works effectively in large dense networks and limits redundant HOs. However, dense environments with a large number of connected users are still severely affected during congestion. Therefore, in the following chapter, we propose a new algorithm which utilises the concept of priority to categorise users. The priority-based Handover algorithm makes smart decisions and guarantees the best services to high priority users. Additionally, these algorithms also ensure reasonable QoE to low priority users by limiting the high bandwidth services.

Chapter 6 Priority Based Handover Algorithm

6.1 Introduction

In this chapter, we propose a Priority Based Handover Algorithm by extending our proposed Software Defined Wireless Network (SDWN) architecture, which utilises the concept of prioritising users to make a smart decision during the process of HO. The Optimised Handover Algorithm for Dense WLAN Environments from chapter 5 underperforms during congestion due to the high density of users and APs in the WLAN network. According to Ozyagci et al [88], the overall throughput falls if the network is over-congested because of the increased number of collisions, which is the case of dense networks. Figure 6-1 illustrates the effect of this density over the throughput. In detail, the figure shows how the throughput eventually decreases due to the increasing number of WLANs per area. Therefore, to overcome this problem of over-congestion, in this chapter, we present an algorithm based on SDWN that extends our previous algorithms. Specifically, this algorithm will prioritise a certain class of users to avoid the effect of the over-congestion.

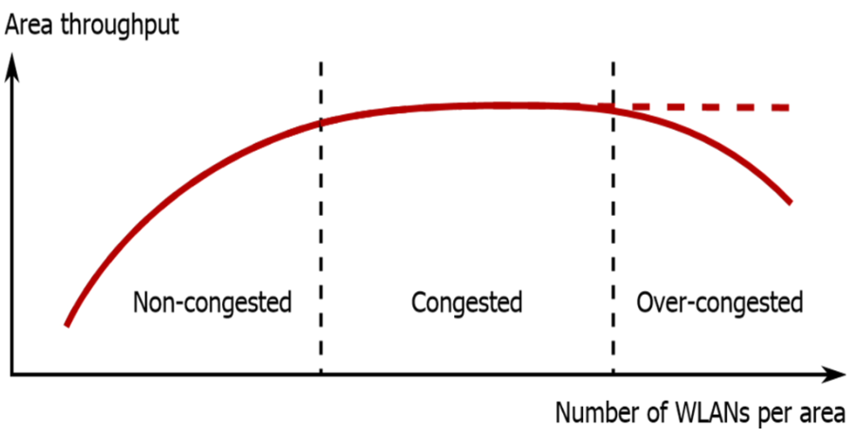

Figure 6-1: Throughput as a function of users and AP density [88]

6.2 High and Low priority-based Solution

In this approach, all users can be classified as high or low priority users. In the case of high priority, the users receive a guaranteed service, while low priority users are affected more during the high traffic periods. However, as we will explain in the rest of this chapter, the proposed solution will also try to optimise the service for low priority users. For instance, in a university campus, a high priority can be given to staff while the students and visitors can be considered low priority users. Similarly, this solution can be extended to any high-density traffic area such as airports, where the high priority users could enjoy, for instance, a premium service with an extra cost.

In this extended algorithm, the controller is able to make a smart decision to provide services to the users through the evaluation of QoS parameters such as BW, Jitter, SINR, and Delay. Specifically, the process involves calculating the status of the network in terms of these parameters and for each low and high priority user, which is currently connected to an AP. The controller makes the final decision by combining the statistics related to QoS parameters with the priority of the users to provide them with services accordingly. The aim is to ensure that high priority users always get guaranteed services and high QoE.

We, therefore, propose the High Priority algorithm at the application layer to provide services to the users based on their priorities. The new approach based on two algorithms, Priority and Multi Criteria Decision Making (MCDM) along with FLCT, enables high priority users to get better QoE while also maintaining an acceptable QoE for the low priority users. The *priority algorithm* is responsible for evaluating the QoE of all the connected users during high traffic periods and identify low priority users which are receiving QoE below an acceptable threshold of 3.1. The low priority users will be sent to a trust queue where the new *MCDM algorithm* comes into play to relocate low priority users from the queue to candidate APs based on their capacity and the distance from the user.

6.3 High Priority-based algorithm

In this section, the algorithm 1 (Priority) is implemented and calculates the QoS of the users. In the following section, algorithm 2 (MCDM) is assembled with algorithm 1 in order to enhance the services for low priority users and show that the two algorithms provide higher performance. In detail, Algorithm 1 is responsible for monitoring and calculating the QoE of all the users in a given time period and evaluates if such a QoE is below the defined threshold, while Algorithm 2 is responsible for making the reallocation decision for those users with QoE lower than the threshold. The proposed algorithms rely on the following parameters:

- U: is a set including all the users connected to the network with any kind of priority, i.e., high or low.
- U_{ϑ}: is a set that contains all the users connected to the network with any kind of priority and experiencing a QoE below the threshold.
- $U_{\vartheta L}$: is a set that contains all the low priority users located in APs where high priority users experience QoE below the threshold.
- U_{TrustQ}: is a set that contains low priority users.
- ϑ: is the threshold, which is set to a MOS value of 3.1.

Algorithm 1 starts by initialising the current parameters (bandwidth, jitter, delay, SINR) for all the users included in set U by using equations (4-1)-(4-6) (lines 1-6 of Algorithm 1). Note that in our simulated scenario, we will consider half the users with high priority and half the users with low priority. In the next step, Algorithm 1 calculates the QoE in terms of MOS based on the above-mentioned parameters for all connected users included in set U (line 7 of Algorithm 1).

Table 6-1: QoS to QoE Mapping extends the previous Table 2-4 to indicate how the MOS is mapped to various levels of QoE according to the conditions as we described in Table 4-2 which specify the QoE rules in mixed scenarios. Afterwards, the controller seeks users with QoE < ϑ during an interval time of 0.2 seconds (lines 8-10 of Algorithm 1). All these users are included in the set U_{ϑ} (line 13 of Algorithm 1). For each AP providing services to the high priority users included in U_{ϑ}, the controller separates the low priority users moving them from U_{ϑ} to $U_{\vartheta L}$ (line 15 of Algorithm 1). If the controller does not find any high priority user below the threshold, it restarts the process. The purpose of separating all low priority users from the pool of connected users is to always maintain the minimum value of 3.1 QoE for high priority users.

Table 6-1: QoS to QoE Mapping

QoS Parameter	MOS				
	Excellent = 5	Very good = 4	Average = 3	Fair = 2	Poor = 1
Delay	≤ 2ms	≤ 4ms	≤ 8ms	≤ 15ms	≥15ms
SINR	≥ = 20dB	≥ = 15dB	≥ = 9dB	≥ = 3dB	≤ = 0dB
Jitter	≤ 20ms	≤ 80ms	≤ 140ms	≤ 200ms	≤ 400ms
BW Video H.320	≥ 900kb/s	≥ 625kb/s	≥ 450kb/s	≥ 220kb/s	≤ 80kb/s
BW VoIP G.711	≥ 64kb/s	≥ 50kb/s	≥ 37kb/s	≥ 24kb/s	≤ 24kb/s

For each user, *i* included in $U_{\vartheta L}$, if it can connect to only its current AP, is moved to the set U_{TrustQ} and it can have only limited resources, i.e., only web browsing (lines 16-18 of Algorithm 1). In the case that user *i* can connect to other APs, i.e., it is located in overlapped areas, it is moved to the set U_{TrustQ} and the controller triggers Algorithm 2 to perform the low priority users' reallocation which is explained below (line 20 of Algorithm 1). Note that these users can be moved again to $U_{\theta L}$ if resources become available, e.g., a high priority user leaves the connection. In the following section we will explain Algorithm 2 in detail.

Algorithm 1 AP Controller

1: **Initialize:**
2: $U \leftarrow$ *No. of users (low and high priority) connected to AP*
3: $B \leftarrow$ *Bandwidth received by user* U_i
4: $J \leftarrow$ *Jitter experienced by user* U_i
5: $D \leftarrow$ *Delay encountered by user* U_i
6: $SINR \leftarrow$ *Signal-to-interference-to-noise ratio of user* U_i
7: **Calculate QoE (B, J, D, SNIR):** by using equations(4 1)-(4 6)
8: **Evaluate the threshold:**
9: **if** $QoE \geq \theta$ **then**
10:     $wait(1)$
11:     *goto* 1
12: **else**
13:     $U_\theta \leftarrow$ *Get users below threshold*
14:     $QoE \leftarrow$ *Estimate QoE based on users below threshold*
15:     $U_{\theta_L} \leftarrow$ *Get users with lowest priority*
16:     $U_{TrustQ} \leftarrow U_{\theta_L}$ *Add lowest priority users to queue*
17:     **if** $AP == 1$ **then**
18:         $U_{TrustQ} \leftarrow$ *Limit resources*
19:     **else**
20:         $U_{TrustQ} \leftarrow$ *Perform user relocation to APs using Algorithm 2*
21:     **end if**
22: **end if**

6.3.1 Low-Priority User Relocation

Algorithm 2 is based on the principle of Multi-Criteria Decision Making (MCDM). The MCDM is the process of selecting the best option from a set of finite decision options. The MCDM is used to make decisions by the evaluation of multiple conflicting criteria. In this case, such a set is defined by the set of candidate APs for the users included in U_{TrustQ}, i.e. the APs providing coverage in the area in which the users are located. The candidate APs provide services to the users and these are required to select while relocating low priority users. Therefore, candidate APs represent the conflicting criteria in the MCDM scenario. The APs are evaluated based on a) the distance from each user included in U_{TrustQ} which denotes (DS) and b) their capacity which denotes (C). The distance between the user and the AP is estimated based on the signal strength (RSSI) received by the user, which starts decreasing whenever the user moves far from the AP.

The purpose of selecting these two parameters DS and C is to best describe the capabilities of the candidate APs in terms of providing the best QoS to the low-priority users included in U_{TrustQ}. The controller starts Algorithm 2 by initialising the parameters DS and C (line 1-4). In the next step (line 5-9), it constructs a decision matrix with the n candidate APs and their calculated parameters DS and C. Therefore, for each AP n among the candidate APs, the controller computes the matrix using DS_n and C_n. Then, the decision matrix, which is called DC, has the form of *m*x*n* and is initialised using the DS and C (line 7 and 8). Here, *m* represents the number of users connected to the AP and the *n* indicates the two parameters DS and C. Next, the DC is standardised and later normalised in order to convert different dimension parameters into dimensionless parameters. After the normalisation, all the parameters will have equal effect in the algorithm. This allows making comparison among multiple conflicting criteria.

Algorithm 2 User relocation to APs

Initialize:
$DC \leftarrow$ *Decision matrix*
$DS \leftarrow$ *Distance from AP*
$C \leftarrow$ *Capacity of the AP*
Construct decision matrix:
for a in AP **do**
  $DC_{mxn} \leftarrow DS$
  $DC_{mxn} \leftarrow C$
end for
Standardize decision matrix (DC):
Calculate weights:
for m in row(DC) **do**
  $t \leftarrow 0$
  for n in col(DC) **do**
    $t \leftarrow t + DC^2_{mxn}$
  end for
  $W_{mx1} \leftarrow \sqrt{t}$
end for
Normalize decision matrix (DC):
for m in row(DC) **do**
  for n in col(DC) **do**
    $DC'_{mxn} \leftarrow DC_{mxn}/W_{mx1}$
  end for
end for
Determine ideal and negative ideal solution:
for r in DC **do**
  $S_i \leftarrow DC'_{mxn}$
  $S_n \leftarrow DC'_{mxn}$
end for
Calculate distance between ideal and negative ideal solution:
Calculate the ideal solution: by using equation (6-2)
Calculate the negative ideal solution: by using equation (6-3)
Evaluate ideal and negative ideal solution:
$DS \leftarrow$ **Minimum value is ideal**
$C \leftarrow$ **Maximum value is ideal**
if Ideal solution found then
  $U_{TrustQ} \leftarrow$ *Perform relocation of users to APs*
  Return to Algorithm 1
else
  goto 1
end if

The standardisation is performed by calculating W, which is the root of the sum of the square of the values in the DC, using two nested loops (lines 12-18 of Algorithm 2). The first loop iterates through the rows of the DC while the second loop iterates through the columns. Firstly, the sum of the square of the values is computed across each row of the decision matrix (as shown in line 15 of algorithm 2) and assigned to variable t on each iteration of the second loop. Then, after all the iterations of the second loop, the square root is computed for variable t and assigned to $Wmx1$ (see line 17 of Algorithm 2). The $Wmx1$ is a one-dimensional array, where, m represents the number of rows in the decision matrix.

Subsequently, each value in the decision matrix is divided by $Wmx1$ to normalise the values. The Eq below computes the normalised DC:

$$DC'_{mxn} = \frac{DC_{mxn}}{W_{mx1}} \tag{6-1}$$

The normalisation will convert different dimension parameters into same scale parameters which will have an equal effect in the algorithm. After the normalisation process, the ideal and negative ideal solutions are calculated using the DC.

In this algorithm, the ideal solution is represented when candidate AP has the least distance from the user and has a high capacity. The opposite of the ideal solution is assumed as the negative ideal solution. As Algorithm 2 proceeds (30-32), the distance of each candidate AP is measured from these ideal solutions using Euclidean distance measure as shown below.

$$DS_i = \sqrt{(DS_{\mathrm{i}1} - DS_{\mathrm{i}2})^2 + (C_{\mathrm{i}1} - C_{\mathrm{i}2})^2} \tag{6-2}$$

Where i is a subset of DS when DS is minimum and C is maximum. While the negative ideal solutions is:

$$DS_n = \sqrt{(DS_{\mathrm{n1}} - DS_{\mathrm{n2}})^2 + (C_{\mathrm{n1}} - C_{\mathrm{n2}})^2} \quad (6\text{-}3)$$

Similarly, n is a subset of DS when DS is maximum and C is minimum. Finally, the candidate APs are ranked based on their relative nearest distance from the ideal solution.

As a result, when Algorithm 2 finds an ideal solution, it performs relocation and assigns U_{Trust} users to the selected AP. The user will be able to get better QoS from the AP which is nearest to the user and has a high capacity. At this stage, Algorithm 2 finalises its operation and returns to Algorithm 1 for further execution (line 36-38). Hence, our contribution lies in proposing a method to construct a decision matrix based on ideal and negative ideal solutions, which assists in relocating low priority users efficiently.

6.4 Simulated Scenario

We have compared the obtained results with our previous FLCT-based and Optimised AP Selection algorithms. Figure 6-2 illustrates the simulated scenario, which consists of 25 APs and 250 STAs. The type of applications that we have again considered are VoIP and Video streaming. In this simulation, we have created 50% of the users as High priority and 50% as Low priority users. Specifically, every 5-10 seconds we created one Low priority and one High priority and distributed them uniformly. The algorithm is triggered only when the received QoE drops below the threshold which will occur just after 130-150 flows to join the network.

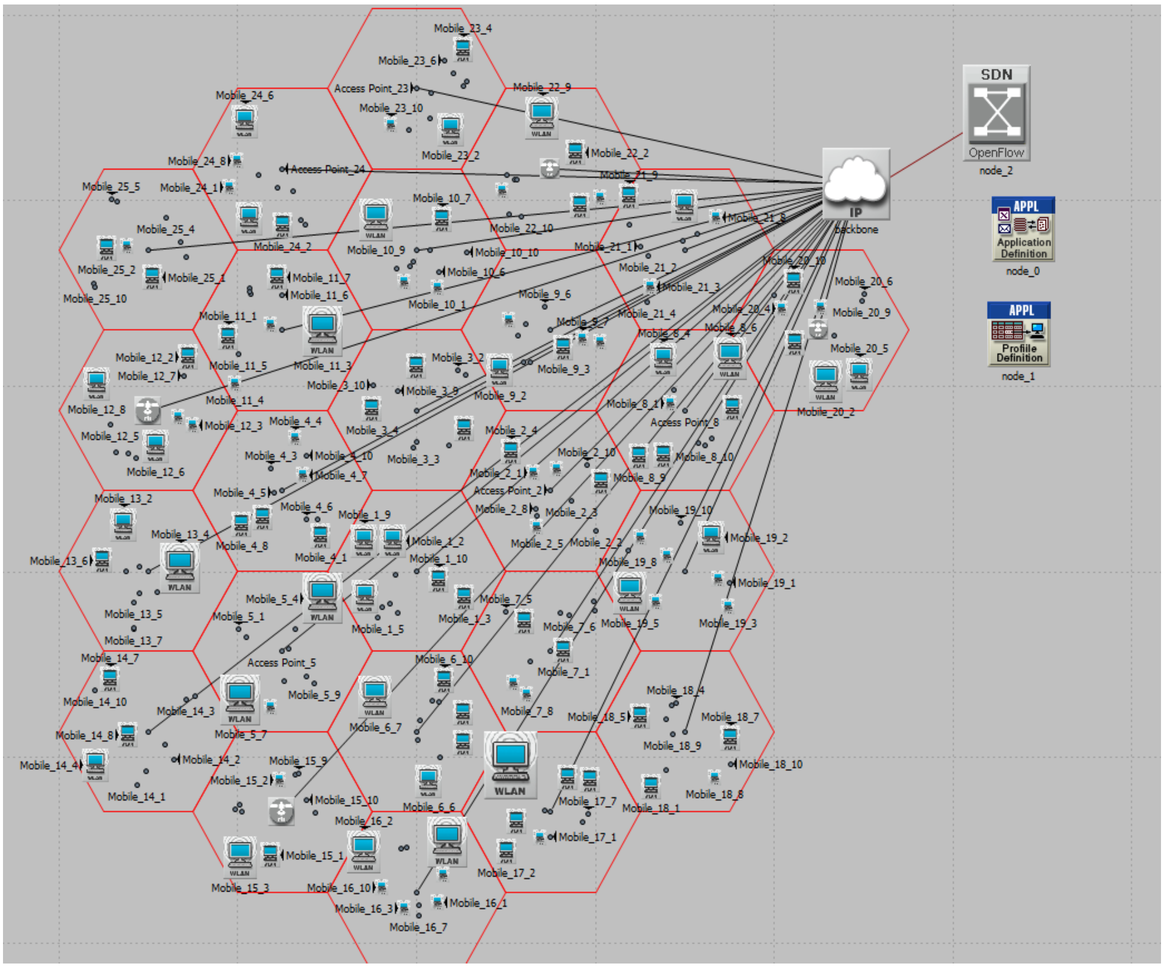

Figure 6-2: Simulated scenario

Figure 6-3 illustrates the result in terms of MOS. Note that we have calculated the MOS for High and Low Priority STAs separately. The blue line shows how the high priority STAs are always above the threshold. However, this result shows a massive drop in the service provided for Low Priority STAs which are represented by a black line. This result has been compared with our previous FLCT-based algorithm, which is represented by a yellow line, we call it here FLCT Best AP Selection, and finally the orange line for Optimised AP Selection.

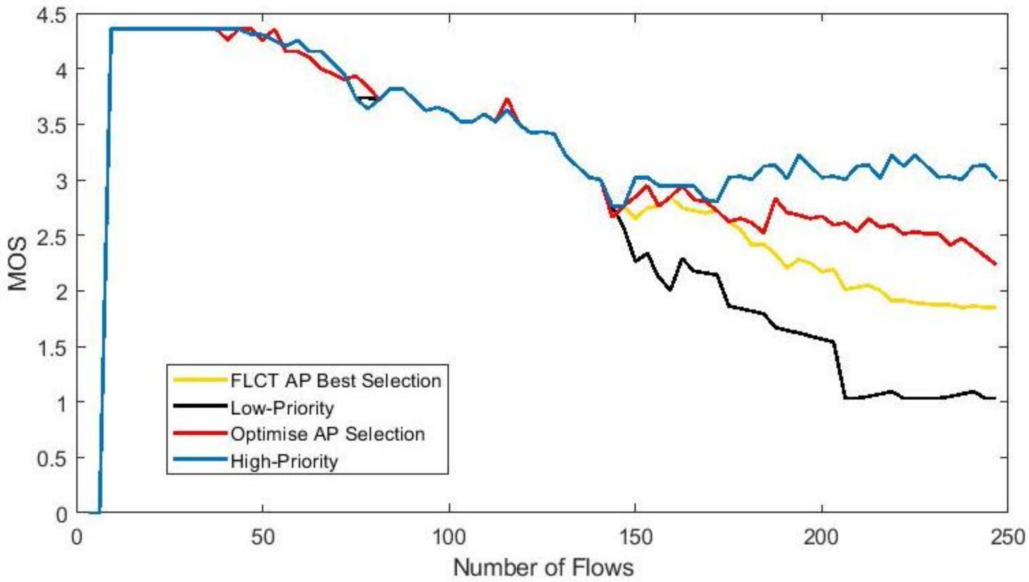

Figure 6-3: MOS

Figure 6-4 shows the end-to-end delay of all the packets received by the STAs. The figure shows how the proposed solution keeps the delay for the high-priority STAs below 200 ms, while for the Optimised AP Selection it is about 400 ms and for the FLCT Best AP Selection, it is about 600 ms. However, the Low-priority STAs experience a delay reaching up to 900 ms.

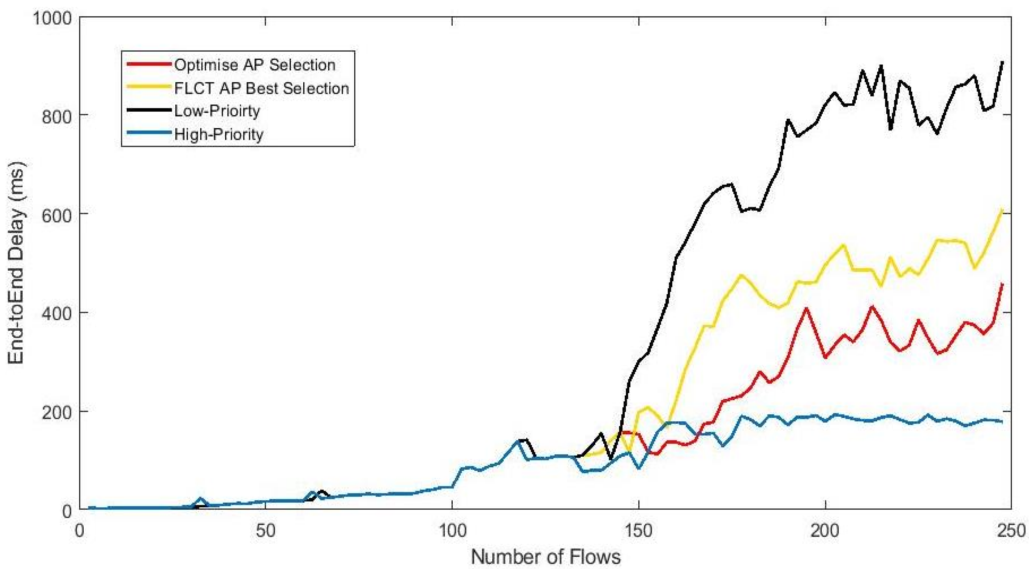

Figure 6-4: Delay

Figure 6-5 shows the average throughput received at STAs. The orange and the yellow lines again represent the average throughput received at STAs in FLCT-based AP Best Selection and Optimised AP Selection respectively. Here the blue line denotes average throughput received at the high priority STAs only in the simulated scenario, while the black line represents the average throughput received at the low priority STAs only.

From this figure, we can observe that STAs with higher priority, get the highest throughput compared with the rest of the solutions. The low priority STAs receive the lowest throughput compared to the FLCT Best AP Selection and Optimised AP Selection algorithms.

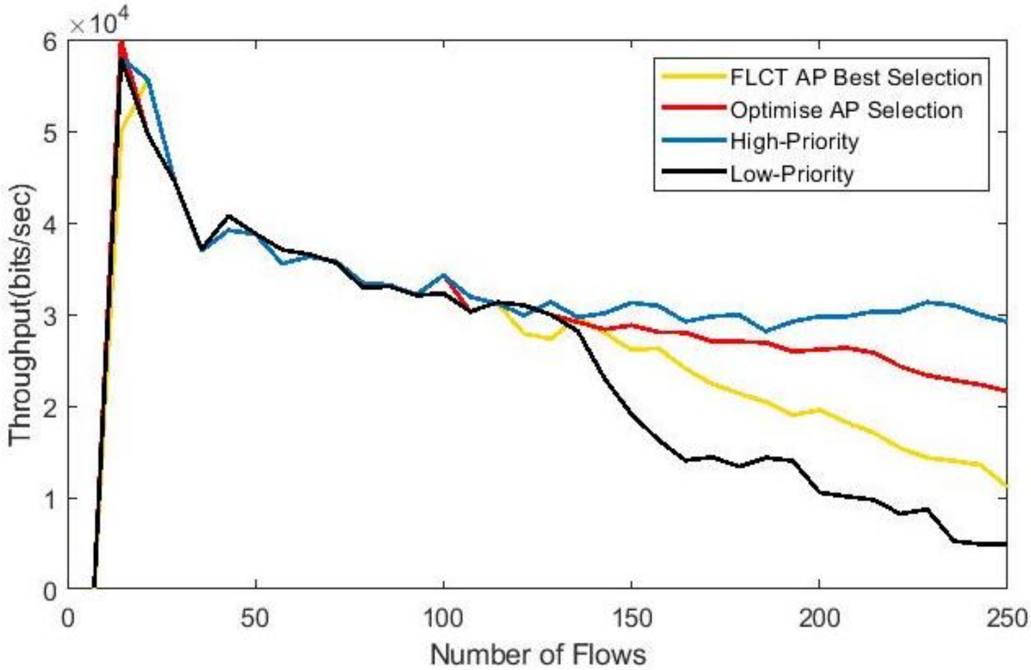

Figure 6-5: Average throughput received at STAs

This result shows that the network could not be further optimised when it becomes over-congested. Moreover, the figures above illustrate the importance of using the prioritisation, which guarantees to high-priority users a satisfactory QoE. However, the low-priority users are severely affected during this process because they experience a reduction of their QoE.

6.5 Summary

This chapter presents a priority-based handover algorithm which is implemented in the application layer. The two algorithms (priority and MCDM) optimise the QoE for the users according to their priorities. Specifically, the concept of prioritising users is introduced in order to always provide the best QoE to the high priority users at the expense of low priority users. However, the proposed algorithms also attempts to maintain an acceptable QoE for low priority users. This is achieved by relocating low priority users to the best candidate APs through the MCDM algorithm. The results of the new approach based on these two algorithms are compared with FLCT-based and Optimised AP Selection. The results indicate that the approach based on our new priority and MCDM algorithms outperforms FLCT-based and Optimised AP Selection and provides better QoE to the high priority users. In the following chapter, we conclude the research work presented in the thesis and provide future directions to further improve our work.

Chapter 7 Conclusions and Future works

This chapter summarises the solutions developed in the thesis and highlights the novel contributions in section 7.1. Additionally, this chapter discusses how the work could be carried out in the future in section 7.2.

7.1 Thesis Summary

In this thesis, we presented and highlighted the limitations of horizontal Handover (HO) solutions in Wi-Fi networks. An extensive body of work regarding HOs can be found in the literature, in terms of resource allocation and mobility management in both homogenous and heterogeneous wireless networks.

In Chapter 1 we presented an introduction that illustrates the massive increase of the smart devices along with the prediction of the data consumption for the next years and we presented the motivations behind the research done for this thesis. Then, we introduced our objectives and the novel contributions of the thesis. Finally, in Chapter 1, we presented the methodology, which is based on the top-down method in order to overcome the proposed research problem.

In Chapter 2 we illustrated the existing solutions dealing with wireless HOs. This includes the concept of the HO, which is made up of the information gathering phase, the decision phase and the execution phase, and the technical details of many HO approaches found in the literature. Then, we discussed in detail the limitations of the existing solutions, such as the lack of awareness of the requirements of the STAs as well as the monitoring methods. Note that, although certain existing HO solutions are able to capture the performance requirements of the STAs, their implementation often results in high complexity. Moreover, such approaches, which focus on a specific performance metric and on a specific wireless technology, cannot be adapted to support other performance metrics, or work on different wireless technologies. Furthermore, we introduced the concept of Quality of Experience (QoE), which has recently become a common metric used in the literature to measure the users' satisfaction. Therefore, QoE is also a crucial parameter to be considered when designing HO strategies in order to guarantee satisfactory services for the users. Finally, in Chapter 2, we explained how the limitations found in the literature could be addressed by introducing centralised and smart functionalities into the network that assist the HO process taking into account these QoE and Quality of Service (QoS) requirements.

In Chapter 3 we explained in detail the concept of centralised and distributed networks and why in this thesis we considered a centralised approach. In addition, we reviewed many studies and solutions based on the centralised Software Defined Network (SDN) and Software Defined Wireless Network (SDWN) approaches. Finally, we illustrated the novel architecture designed and developed for this thesis based on the SDWN paradigm able to support QoS and QoE-aware HO algorithms.

In Chapter 4, we introduced our QoE Oriented Handover algorithm, which relies on the Fuzzy Logic Control Theory (FLCT) concept. In addition, we discussed in detail how this algorithm can support seamless HO considering the user's QoS and QoE requirements. Moreover, in Chapter 4 we showed how our solution successfully improves the standard by a gain of 17% and another algorithm considered in the state of the art by a gain of 11%. Additionally, we explained the main limitation of this algorithm, which provides limited scalability in the case of large networks.

In Chapter 5, we presented the Optimised Handover Algorithm for Dense WLAN Environments. Moreover, we explained the concept of the Adaptive Hysteresis Value (AHV) and how it helps avoid unnecessary HOs. In addition, we described how this algorithm works efficiently in dense WLAN networks and we showed a gain of roughly 33% in terms of the end-to-end delay achieved by applying our proposed solution compared to the FLCT-based approach. Finally, we discuss how this algorithm is negatively affected in dense environments with a large number of connected users.

In Chapter 6 we then introduced our Priorities Based Handover Algorithms, which utilise the concept of users' prioritisation that can make smart decisions during the process of HO. Specifically, the concept of users' prioritisation is introduced in order to always provide the best QoE to users with high priority. In this chapter, we explained the two algorithms that we have used in this approach. According to our proposed algorithms presented in chapter 4 and 5, the throughput was roughly 35kbps. However, the new solution based on the Priorities Based Handover Algorithms uses the priority concept for low and high priority users and provides considerably higher throughput reaching 45kbps as compared to previously proposed algorithms.

7.2 Future Works

This subchapter addresses the future work that will extend the solutions presented in this thesis in order to provide new innovative approaches such is using scenarios in a more dynamic environment including users mobility. Specifically, future work can be summarised as follows:

I. **Extend the proposed algorithms to support heterogeneous networks in dynamic areas:** The current architecture has been designed to support homogeneous networks managed by the same network provider. Therefore, this architecture will be extended in order to also support vertical HO strategies by involving LTE networks supporting users at the movement which is considered more challenging in the HO process.

Therefore, the new architecture will be tailored for two different network environments, i.e., WLAN and LTE. In this context, the designed SDWN controller will be extended in order to handle the following LTE components:

- Home Subscriber Server (HSS), which is the main data store of the system. Specifically, it stores all the information about the subscribers such as user profile, identification, registration and network authorisation information [89].
- Proxy Call Session Control Function (P-CSCF), which will act as a proxy server for the users, i.e., for receiving and forwarding from and to users the Session Initiation Protocol (SIP).
- Interrogation Call Session Control Function (I-CSCF), which is responsible for routing the request to the right server once the request obtains authentication and authorisation [90].
- Serving Call Session Function (S-CSCF), which is the heart of the core network and will act as an SIP registrar server, controlling and routing paths for mobile terminated sessions.
- LTE gateway switch and WLAN gateway switch, which will act as bridges between LTE and WLAN networks.

The extended architecture will require three SDWN controllers. The first controller will be on top of the WLAN network, the second controller will be on top of the LTE one. A third controller, called the super controller, will act as a bridge between the WLAN network and LTE network. The role of the super controller will be managing operations between WLAN and LTE such us roaming authorisation, handover, tracking area location and real-time monitoring of all the users' status and requirements.

II. **Extend the proposed solutions by including Machine Learning (ML)-based approaches:** We believe that using ML along with MIMO and beamforming will allow us to enhance this work. Specifically, the use of MIMO will increase the capacity dramatically alongside using the beamforming techniques. The beamforming technique is described as antenna arrays with a signal processing algorithm. Those antennas used for transmitting and receiving signals in massive MIMO systems. The gained beams in the spatial dimension are generally formed by balancing the weighting of the antennas according to set rules. The different antenna weights lead to constructive interference in some directions and destructive interference in other directions due to the phase and gain differences between the signals in different antennas. Additionally, the ML concept will improve the HO decision through prediction techniques, which will help to optimise the network management complexity by reducing, for instance, the messages exchanged among the modules of the proposed architecture during the HO execution. ML techniques will also allow us to predict in advance when users will require an HO and how much resources they will need. These ML techniques include statistical as well as advanced Deep Learning techniques. As the data volume will increase in the future, the Deep Learning techniques will be able to learn the correlation between various factors i.e. bandwidth and latency and provide high prediction accuracy for the most efficient HO. In addition, the ML concept will improve the proposed algorithms by including self-awareness and self-organisation, which will improve the network management in terms of reducing the cost of installation, operations, administrations and maintenance activities.

7.3 Concluding Remarks

The approach presented in this thesis introduces an SDWN Architecture for Wireless Network Engineering to Support a Quality of Experience Aware Handover. As a result, many of the existing HOs limitations are associated with lack of awareness of QoS and QoE requirements and they do not scale well with the size of the network. By using a centrally controlled network, and QoS and QoE awareness, we were able to identify the user requirements and use MOS as the score to maintain user satisfaction. This novel approach provides numerous enhancements over existing solutions by guarantee the best possible connectivity to the users in terms of their QoE and QoS requirements. Additionally, we considered a large-scale network where the network is over-congested. We have optimised the HO via reducing the ping-pong effects and reducing the unnecessary HO. We have achieved this optimisation via taking into consideration Adaptive Hysteresis Value (AHV). This algorithm has been designed to address dense network environments and outperforms existing methods. However, dense network environments with a large number of connected users are still severely affected during over-congestion. Therefore, it was essential to introduce a concept of prioritising users. It prioritises a certain class of users to avoid the effect of the over-congestion and guaranteed high QE service into the high priority users. The results illustrate that the approach based on priority outperforms the state of the art and provides better QoE to the high priority users despite the over-congestion situation.

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