Call Handover Prediction and Handoff Prioritization Using Users' Call History

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14 October 2019

Submitted to the Department of Electrical Engineering at the University of Cape Town in partial fulfilment of the academic requirements for a Bachelor of Science degree in Electrical Engineering.

Key Words: Vertical Handover, Predictive Algorithms, Heterogeneous Wireless Networks

Declaration

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Terms of Reference

ID:	**OF-8**
SUPERVISOR:	OE Falowo
TITLE:	Call Handover Prediction and Handoff Prioritization Using Users' Call History
DESCRIPTION:	In mobile networks, it is important to prioritize handoff calls over new calls. However, the adequate level of priority required for handoff calls over new calls depends on the average mobility rate of network users. Thus, analysis of users' call history can provide information about individual user's mobility rate, and the information can be used to predict call handover rate and the level of priority required for handoff calls. The purpose of this project is to develop a predictive algorithm for making decisions on prioritization of handoff calls in mobile networks.
DELIVERABLES:	A review of call handover predictive algorithms, algorithm, simulation codes, simulation results, and report.
SKILLS/REQUIREME NTS:	MATLAB, Java, or any other programming language, EEE4121F/EEE4087F
ELO1: Problem solving: *Identify, formulate, analyse and solve complex* engineering problems creatively and innovatively*	*(Explain what needs to be done to meet the ELO requirement)* The student is expected to design and implement a predictive algorithm for prioritizing handoff calls.
ELO 4: Investigations, experiments and analysis:** *Demonstrate competence to design and conduct investigations and experiments.*	The student is expected to investigate the performance of the slice handover algorithm through numerical simulations.
EXTRA INFORMATION:	For a student interested in pursuing a master's degree, the project can be expanded to an MSc dissertation.
AREA:	Wireless Networks

Acknowledgements

I acknowledge my supervisor, Associate Professor Olabisi Falowo for guiding me in conducting this research project. I would also like to express my gratitude to my mother Mrs Mukandi, my brother Tichaona Mukandi and my sister Joyce Munyanduki for their moral and financial support they gave me throughout my undergraduate degree. This work would not have been possible without their contribution.

Above all, I would like to thank Almighty God for giving me the strength and grace to carry out this research project.

Abstract

Multi-mode mobile terminals (MTs) have become ubiquitous exceeding 5 billion users globally. Use of multi-mode MTs in heterogeneous wireless networks (HWNs) enables end-users to roam between the available radio access technologies (RATs). An end-user making a call from a multi-mode MT may trigger a vertical handover (VHO) in the HWN if the current serving RAT does not support the incoming call. VHOs in a HWN are expensive thus it is vital to keep the number of VHOs as low as possible. Studies carried over the years on investigation and analysis of mobile phone subscribers call history datasets have revealed some interesting characteristics which suggest that most users follow recurring call patterns.

In this research project, a predictive call history-based algorithm that anticipates VHOs and minimizes the number of VHOs in HWNs is proposed. The algorithm is evaluated using a HWN model featuring four RATs. Multi-mode MTs with single homing capabilities and only support voice, data and video calls are used.

The proposed algorithm is compared with a non-predictive algorithm, which can only avoid VHOs by chance. Results from the simulations reveal that the proposed VHO prediction algorithm successfully decreases the number of VHOs thus high priority is given to handover calls. However, the downside of the proposed algorithm is its potential uneven distribution of load.

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Glossary

VHO	Vertical Handovers
MNO	Mobile Network Operator
HWN	Heterogeneous Wireless Network
QoS	Quality of Service
G	Generation
1G	First Generation
2G	Second Generation
3G	Third Generation
4G	Fourth Generation
5G	Fifth Generation
RAT	Radio Access Technology
AMPS	Advanced Mobile Phone System
FDMA	Frequency Division Multiple Access
TACS	Total Access Communication System
ETSI	European Telecommunication Standard Institute
GSM	Global System for Mobile Communications
TDMA	Time Division Multiple Access
CDMA	Code Division Multiple Access
GPRS	Enhanced Global Packet Radio System
EGPRS	Enhanced Global Packet Radio System
EDGE	Enhanced Data Rate for GSM Evolution
UMTS	Universal Mobile Telecommunications System
3GPP	Third Generation Partnership Project
WLAN	Wireless Local Area Network
IP	Internet Protocol
QoE	Quality of Experience
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
PoA	Point of Access
MT	Mobile Terminal
MADM	Multiple Attribute Decision-Making Algorithms
MEW	Multiplicative Exponent weighting
GRA	Gray Relational Analysis
SAW	Simple Additive Weighting
VIKOR	VlseKriterijumska Optimizacija I Kompromoso
AHP	Analytical Hierarchy Process
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
ELECTRE	Elimination et Choix Traduisant la REalité
ANN	Artificial Neural Network.
RSSI	Receiver Signal Strength Indicator
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access

Chapter 1 : Introduction

1.1 Background to the study

The advent and evolution of mobile wireless networks through various generations led us to an era where handheld mobile computing devices have become the predominant choice for most users. In [1] Cisco reported that by 2021 the global mobile traffic is expected to grow about fivefold the numbers recorded in 2017 to a staggering 50 exabytes per month *(1 exabyte =* 10^8 *bytes)*. MNOs are faced with the challenge of supporting the growing number of end-users without a compromise on the perceived quality of experience (QoE) and quality of service (QoS).

Data traffic offloading to heterogeneous wireless networks (HWN), among other solutions, has been a successful solution to handling the increasing data traffic. HWNs feature multiple dissimilar radio access technologies (RATs) interoperating in the same environment to provide ubiquitous coverage to end-users at all times. Most end-users are equipped with heterogeneous mobile terminals to enjoy the full rewards of HWNs. However, one of the biggest challenges faced by MNOs in HWNs is handover management. Use of heterogeneous mobile terminals (MTs) in HWNs means users will be able to switch between RATs thus there is a possibility of a lot of vertical handovers (VHOs).

VHOs in HWNs can be triggered *(1)* when a MT loses its connection with the serving RAT *(2)* when there is need to switch to a better RAT *(3)* when serving RAT needs to offload traffic to other RATs for load balancing *(4)* due to the call dynamics of a heterogeneous MT [2]. VHOs in a HWN are very costly due to the potential packet loss and additional processing overhead incurred. Thus minimizing the number of VHOs is crucial and ensures effective resource utilization.

In [3] an analysis done on users' mobile phone call logs reveals some interesting characteristics and behaviors of mobile phone subscribers. The study reveals that end-users have common calling patterns in a network. It is evident that if any mechanism is able to anticipate and predict VHOs and network resource allocation was done in advance, the number of vertical handovers can be significantly reduced.

In this study the call dynamics of heterogeneous MTs and their effect on vertical handovers in HWN is investigated. A call history-based predictive algorithm which reduces the number of VHOs is proposed.

1.2 Objectives of this study

1.2.1 Problems to be investigated

In mobile wireless networks handovers are expensive and it is important to prioritize handover calls over new incoming for better end-user experience. The objective of this study is

- Investigate and review existing call handover predictive algorithms.
- Develop an algorithm handover algorithm that uses users' call history to predict handovers and prioritizes handover calls.
- Evaluate the performance of the developed algorithm

1.2.2 Purpose of the study

The purpose of this study is to investigate the call dynamics of a single-homed, multi-mode MT in a HWN and develop a users' call history-based vertical handover prediction algorithm that prioritizes handover calls by minimizing the number of necessary VHOs in HWNs. Vertical handovers in a network are very expensive and minimizing them has the following advantages

(1) Reduction in the overhead caused by handovers.
(2) Avoiding superfluous handovers.
(3) Effective network resource utilization.
(4) Provisioning of a guaranteed QoE and QoS which meets end-users' requirements.
(5) Reduction in power consumed due to handovers.

1.3 Scope and Limitations

The developed algorithm is suitable to use in a HWN featuring multiple RATs supporting different services. This study is only limited to users with single-homed, multimode mobile terminals. The mobile terminals are only limited to a single connection with one RAT at a time.

Due to data privacy issues, real-life subscribers' call history datasets could not be obtained. Thus the users' call history logs generated and used in this work might not truly reflect call patterns in a realistic environment.

The study is only limited to the prediction of the MTs next-state when a new call that marks the start of a new call session is made. Prediction of subsequent states during an ongoing session is outside the scope of this study. .

1.4 Plan of development

The rest of the report is structured as follows.

Chapter 2: Presents a literature review of related works. The Chapter starts with a description of the evolution of mobile wireless network generations followed by a discussion on HWNs and heterogeneous MTs. Furthermore, a discussion of call handover management in HWNs is presented and then the chapter ends with an analysis and evaluation of existing VHO algorithms.

Chapter 3: Presents a model for the HWN and call dynamics of a single-homed multi-mode mobile terminal supporting 3 services namely voice, data and video.

Chapter 4: Presents a detailed design of the proposed call history-based one-step forward predictive vertical handover algorithm.

Chapter 5: Provides implementation details of the proposed algorithm and development of the simulation.

Chapter 6: Presents results from the simulations carried out as well as a detailed analysis and evaluation of the proposed predictive algorithm.

Chapter 7: Outlines the conclusions drawn from the analysis carried out on results.

Chapter 8: Outlines the recommendations for future work.

Chapter 2 : Literature Review

2.1 Mobile Wireless Networks

Evolution of Mobile Wireless Networks

The telecommunications industry has witnessed a rapid advancement and evolution of mobile wireless technologies through a series of innovations (also known as the network generations) as MNOs' aim to provision satisfactory QoS that meets the requirements of end-users. Each network generation (G) is characterized by a change in the radio access technology (RAT) hence different wireless network performance metrics which include coverage, capacity, speed, security and bandwidth [4].

The first generation (1G) mobile wireless networks supported only voice calls via analog radio transmission. The second-generation (2G) provided additional support for messaging and migrated to the use of digital radio transmission. The third-generation (3G) was developed to support the proliferation of smart devices thus supported data services with increased data capacity and speeds. The fourth-generation (4G) aimed to integrate 3G with fixed internet support to wireless networks.
The launch of fifth-generation (5G) is expected to take place in 2020 and 5G is expected to revolutionize the telecommunications industry by offering data rates that are multitudes faster than 4G networks [10].

2.1.1 First Generation Networks (1G)

The First-Generation Networks emerged around the 1980s. The 1G network standard was based on an analog radio transmission technology called Advanced Mobile Phone System (AMPS) which was developed by AT&T, a telecommunication company based in the United States of America. AMPS only supported voice services and used circuit switching in its network core. AMPS used frequency modulation to transmit radio signals using Frequency Division Multiple Access (FDMA) techniques.
In 1985 the United Kingdom introduced its own derivative of AMPS called Total Access Communication System (TACS) which had a reduced bandwidth hence reduced signaling rate. Like all analog systems, the 1G networks were susceptible to noise and static, required bulky mobile equipment and prone to eavesdropping [5]. The 2G network standard, its successor, was developed to address some of the shortcomings of the 1G network standard.

2.1.2 Second Generation Networks (2G)

In the late 1980s, the European Telecommunication Standard Institute (ETSI) developed the second generation of mobile communication systems based on a digital RAT called Global System for Mobile Communications (GSM). Similar 1G, GSM technology used circuit switching in its network core using Code Division Multiple Access (CDMA) and Time Division Multiple Access (TDMA) techniques. GSM became a worldwide success and it is still operational to date. As a result of its popularity adaptations and further improvements of GSM resulted in semi generation technologies Global Packet Radio Service (GPRS) and Enhanced GPRS (EGPRS) also referred to in literature as 2.5G and 2.75G respectively. Both GPRS and EGPRS used packet switching in their network core and this provided further support for services such as web browsing. Packet switching also enabled Mobile Network Operators to bill its subscribers based on data usage rather than time-based billing. The need to improve the data rates and QoS resulted in the introduction of Enhanced Data Rate for GSM Evolution (EDGE) which was a further improvement of the 2G network standard. Despite the significant boost in data rate that came with the introduction of EDGE, the 2G network standard was still suboptimal when it came to handling complex data such as video. The growing demand for internet services and need to meet the QoS requirements of these internet services led to the birth of third generation (3G) networks. [5][4]

2.1.3 Third Generation Networks (3G)

The introduction of the 3G network in the early 2000 was triggered by the need to address the limitations of 2G networks, increase demand for internet services at higher data rates as well as a need for a global mobile communication system. The 3G network standard was developed to be downward compatible with earlier RATs such as GSM and EDGE. This was important as it enabled the interoperability of earlier and newer RATs heterogeneously in the same environment. The Universal Mobile Telecommunications System (UMTS) technology, developed by the Third Generation Partnership Project (3GPP) became the most successful implementation of the 3G standard. UMTS employed packet switching in its network core. The 3GPP made further enhancements of UMTS, which led to the release of High-Speed Download Packet Access (HSDPA), High-Speed Uplink Packet Access (HSUPA). HSDPA and HSUPA enabled users to experience improved uplink and downlink speeds. It was also around this time when Wireless Local Area Network (WLAN) standards like IEEE 802.11a/b/g/n gained popularity. Several network congestion protocols and load balancing protocols were developed by the 3GPP to provision better QoS through offloading cellular network traffic to the WLAN networks during traffic congestion and at high loading [5]. The 3G network standard remained competitive for several years. However, at the time of its introduction researchers had already started working on the development of the Fourth Generation (4G) network standard with an aim to migrate to an all IP packet-based optimized system that supports higher data rates, lower latency and coexistence of multiple RATs.

2.1.4 Fourth Generation Networks (4G)

The 4G standard was aimed at provisioning an all-Internet Protocol (IP) based packet-switched network with enhanced QoS and quality of experience (QoE) through high data transmission rates, broader bandwidth, higher channel capacity, higher spectral efficiency and coexistence of multiple RATs within the same environment [5]. The coexistence of multiple RATs heterogeneously gave users the flexibility to choose services based on their personal preferences. The 3GPP developed an implementation of the 4G standard called Long Term Evolution (LTE). LTE employed advanced, novel mobile telecommunications technologies at that time such as Carrier Aggregation (CA), Coordinated Multipoint Operation Multi-users Multi-input Multi-output (MIMO) antennas and Cooperative Relay Transmission. The 3GPP released further improvements of LTE namely Long-Term Evolution Advanced (LTE-A) followed Long-Term Evolution Advanced Pro (LTE - Advanced Pro) [3].

2.1.5 *Fifth Generation Networks (5G)*

The 5G standard is the next generation network and is set launched in 2020 [5]. 5G technology is set to revolutionize and open up a new era in the mobile telecommunications industry by providing innovators with endless possibilities. The 5G network is expected to integrate technologies such as Network Functions Virtualization (NFV), Next Generation Protocols (NGP), Multi-Access Edge Computing (MEC), Millimetre Wave Transmissions (mWT), Software Defined Networks (SDN) and the Internet of Things (IoT). 5G will use a virtualization technique called Network Slicing which allows multiple logical and independent network slices to run on the same shared network infrastructure with each slice tailored to serve specific applications which differ in their requirements [8]. Network slicing will significantly improve the users' QoE and QoS. The 5G standard is envisaged to enable Mobile Network Operators (MNOs) to offer new services to new categories of users. Figure 2.1 shows some of the new services to be offered to new categories of users by MNOs in 5G networks.

Figure 2.1: List of new services to be offered to new categories of users by mobile network operators in 5G Networks.

However, MNOs face a number of challenges on migrating to 5G networks and some of the challenges are described below

(1) **Small cell deployment challenges** - MNOs may face stringent regulations and policies from local authorities around small cell deployment. These excessive financial and administrative obligations, as well as lengthy procurement procedures on MNOs, tend to curtail innovation and block investment.

(2) **Privacy and Security -** The 5G networks will have data rates magnitudes faster than the existing 4G networks thus an increase in connectivity between devices and services is expected. As a result, 5G networks must be able to ensure data is protected against the growing sophisticated cybersecurity threats.

(3) **Spectrum Challenges** - Deployment of 5G networks poses a challenge to telecommunication organizations in the identification and allocation of the globally harmonized spectrum across a range of spectrum. Harmonized allocation is essential in effective utilization of bandwidth, limiting interference along borders and facilitating international roaming.

(4) **Cost of deploying 5G infrastructure** - The deployment and mass adoption of 5G networks is expected to face initial challenges similar to those faced by the adoption of LTE. This is because 5G involves building new infrastructure rather than just building a layer on top of existing infrastructure [6].

(5) **Availability of 5G compatible devices** - The availability of 5G compatible devices is critical in generating end-user demand for its services at the time of its launch. Manufacturers need to develop 5G capable MTs that are backward compatible with 2G, 3G, and 4G networks and make them available by 2020. The battery life of these devices is also critical for best performance with the expected myriad of 5G services.

Figure 2.2 illustrates the stages of progression of mobile wireless network generations and a summary of the above-mentioned mobile wireless network generations is provided in Table 2.1

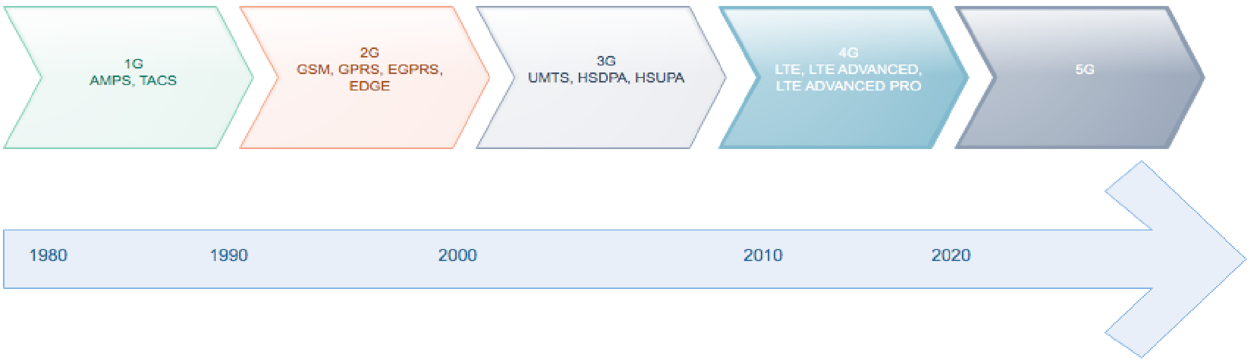


Figure 2.2: Illustration of the stages of progression of mobile wireless network generations from 1G to 5G.

Table 2.1: Summary of the above-mentioned generations of mobile wireless network technologies.

Network Generation	**1G**	**2G, 2.5G, 2.75G**	**3G**	**4G**	**5G**
Transmission Method	Analog	Digital	Digital	Digital	Digital
Services	Voice calls only	Voice calls and SMS (2G), additional support of MMS and Mobile internet in 2.5G and 2.75G	Voice calls, SMS, Multimedia Messaging, Mobile internet, video and audio streaming	Voice , SMS, Multimedia Messaging, mobile internet, data, video and audio streaming, Mobile television (HD)	high data rates in Gbps, high channel capacity
Data Rate	2Kbp	Up to 64Kbps	Up to 2Mbps	1Gbps	>1Gbps
Mobility	Poor	Medium	Medium	High	Very High

2.2 Heterogeneous Wireless Networks

Heterogeneous Wireless Networks

A Heterogeneous Wireless Network (HWN) environment is characterized by the coexistence of multiple dissimilar RATs providing ubiquitous network coverage to users at all times. In HWNs, MNOs aim to exploit the benefits of different RATs. End-users must be equipped with heterogeneous MTs to enjoy the benefits of HWNs. Figure 2.3 below shows the coexistence and overlapped coverage of 3 different RATs in a HWN.

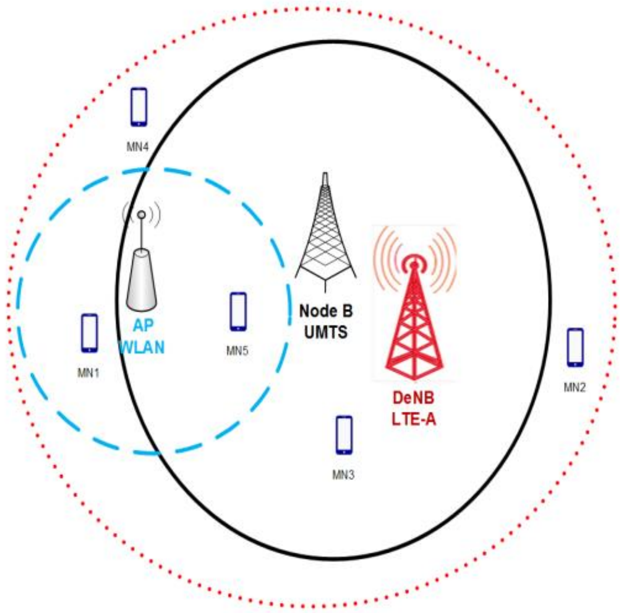


Figure 2.3: An Example of a heterogeneous wireless network.

2.2.1 Motivations for Heterogeneous Wireless Networks

(1) No single RAT can simultaneously meet all the QoS requirements of existing diverse mobile wireless network services and applications. Each RAT has its own limitations in terms of services and applications supported, security, cost, latency and speed [10]. The need to inclusively harness the different advantages and capabilities of different RATs in the same network environment led to the concept HWNs.

(2) Due to the time and resources invested by MNOs in deploying earlier RATs as well as the need to keep support for users with older MTs, MNOs are very reluctant to do a complete phase-out of the earlier technologies.

(3) A system that allows coexistence and interoperability of multiple dissimilar RATs is beneficial to end-users as it offers them the flexibility to select the type of RAT/service based on their needs such as pricing and data rates. Many end-users always want to switch to the network with the best perceived QoE.

2.3 Heterogeneous Mobile Terminals

2.3.1 Mobile terminal heterogeneity

MT heterogeneity is defined as the difference in MT with regards to factors shown in Figure 2.4. Use of multi-interface MTs allow end-users the freedom to roam across RATs to ensure that MT is always connected to the most optimal RAT that best suit their requirements. The best RAT depends on several aspects such as end-user preferences, MT capabilities, network coverage, available resources, QoS requirements of services, security and MNO policies. [10][60]

Figure 2.4: Mobile terminal heterogeneity.

2.3.2 Mobile Terminal Modality

The number of network interfaces available to a MT and the type of RATs the MT supports is referred to as MT modality [10]. Figure 2.5 shows an example of 3 MTs with different modalities in a 3 RAT HWN. MT-2 has two network interfaces that support only connectivity with RAT-2 and RAT-3 thus it has modality of 2 (dual-mode). MT-3 has one network interface that supports RAT-3 only, thus its has modality 1 (single mode).

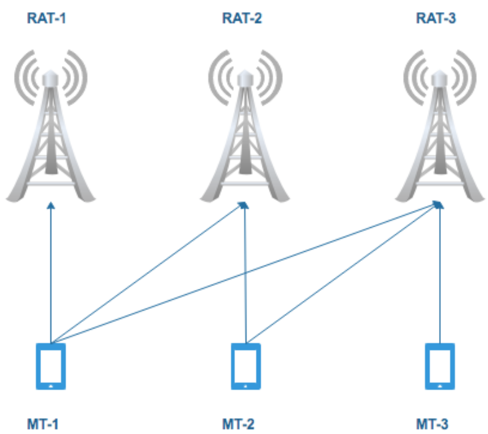


Figure 2.5: Illustration of Mobile Terminal Modality.

2.3.3 Mobile terminal homing

Multi-homing enables a MT with multiple network interface cards to simultaneously maintain several connections in parallel allowing it to receive packets from different RATs Figure 2.6 shows an example of 3 MTs with different homing capabilities existing in a 3 RAT HWN. MT-1 has network interfaces to support a support all the RATs but can only simultaneously connect to RAT-1 and RAT-3 to support the same application thus it is a triple-mode, dual-homed device. [10][14-15].

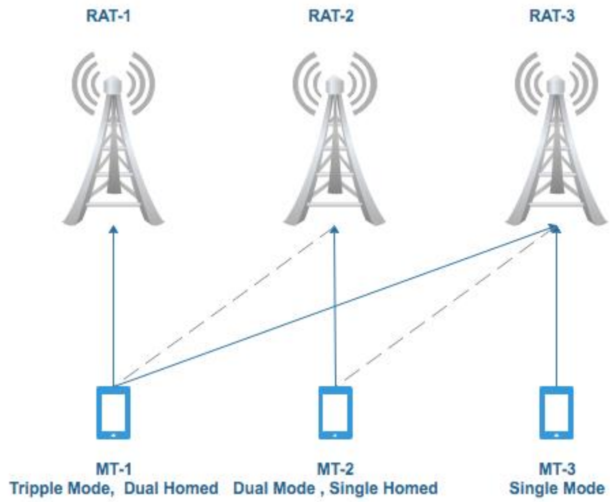


Figure 2.6: Illustration of mobile terminal homing.

2.4 Call Handover Management in Heterogeneous Wireless Networks

The European Telecommunications Standards Institute (ETSI) defines call handover as the mechanism by which a MT changes is Point of Access (PoA) in a network while maintaining a defined bearer service QoS. Figure 2.7 illustrates the major classifications of call handovers found in literature [18 - 19][25]. The next section describes some of the major classifications of call handovers in HWNs.

2.4.1 Classification of Call Handovers

Handovers can be classified into horizontal and vertical handovers based on the type of RATs involved. In horizontal handovers, MT changes its PoA from a source to target system employing the same RAT whilst vertical handovers involve the change of MT's PoA to a target system employing a different RAT to the source (such as UMTS to LTE)**.**

Call handovers can also be classified into soft and hard handovers based on the number of connections involved during the handover execution process. During a soft handover, the MT maintains its connection with the old PoA while establishing a connection with the new PoA. Hence also known as *'make before break'* handovers. In contrast, hard handovers break their connection with source PoA before establishing a connection with a new PoA thus also called '*break before make*' handovers. The change in MT's PoA may result in MT staying within the same domain (intra-domain handover) moving to another domain (inter-domain handover).

A further classification of handovers can be made by considering the entity involved in triggering the handover procedure. Handovers triggered by the MT are classified as Mobile Initiated Handovers whilst those triggered by the network are referred to as Network Initiated Handovers. Furthermore, classification can be based on whether the handover process is controlled by the MT or a network entity hence mobile-controlled and network-controlled handovers respectively.

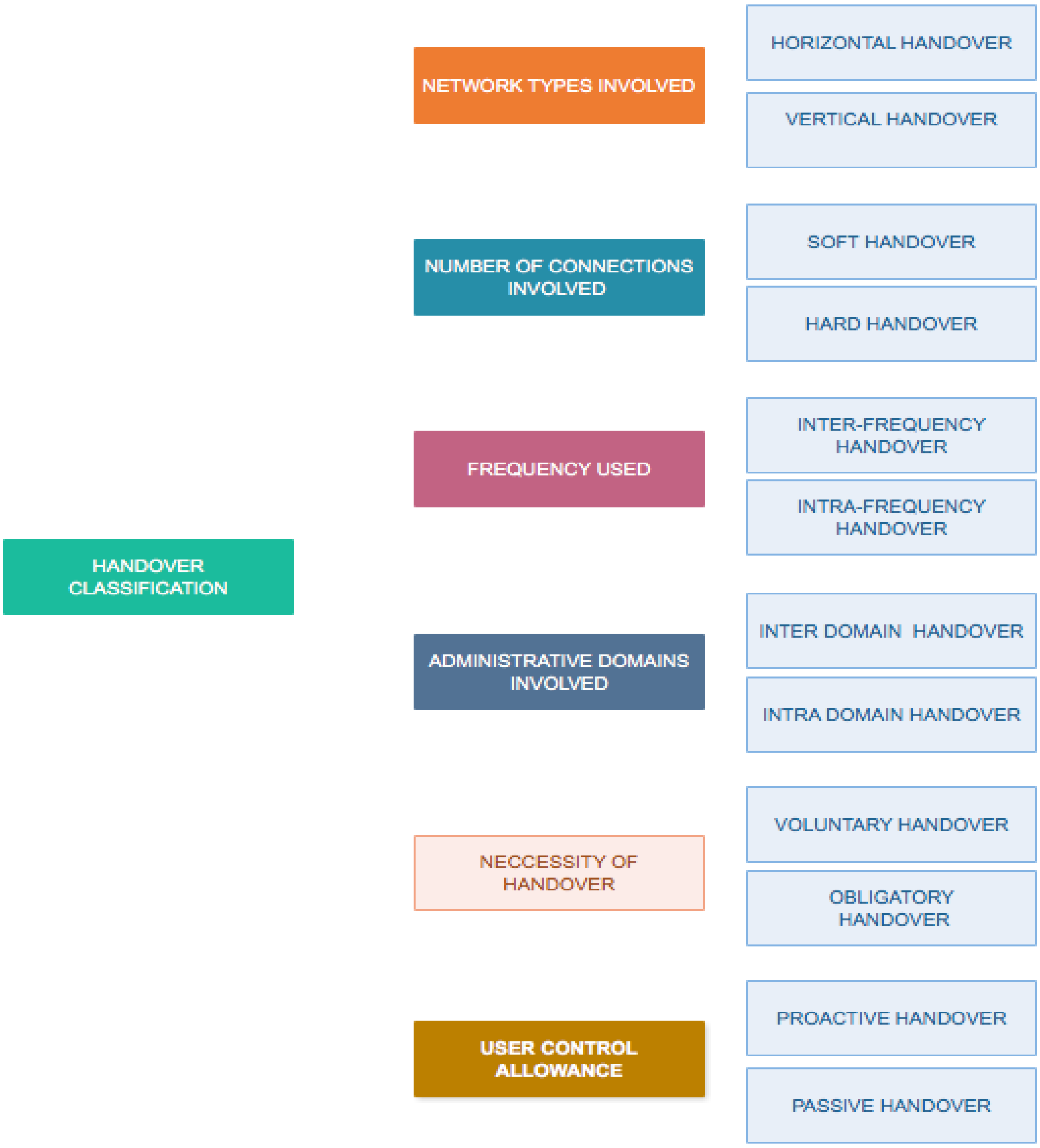


Figure 2.7: Classification of call handovers in heterogeneous wireless networks.

This study is mainly focused on vertical handovers in a HWN therefore from this point thereafter any mention of call handover will be referring to vertical handovers.

2.4.2 Vertical handover procedure in heterogeneous wireless networks

The VHO procedure can be divided into three main phases [20 - 22].

(1) Information acquisition phase,
(2) Handover decision-making phase
(3) Handover execution phase

(4) **Information Acquisition Phase -** The main aim of the information acquisition stage is for the MT with multiple network interface cards to identify the RATs and services available in the HWN. Information acquisition can be conducted regularly by allowing MT to frequently probe the network for information or it may be triggered by events that signify an imminent handover. In the former case, it is important to note that the higher the frequency of MT probing the network the lower the reachable network discovery time however at the expense of lower battery life for the MT.

(5) **Handover Decision-Making Phase -** The handover decision-making phase serves the purpose of deciding the optimal target RAT from a pool of alternative RATs and when to trigger the handover. The target RAT is selected using algorithms that take into consideration different criteria. For an intelligent handover decision, handover decision parameters used by the handover decision algorithms must be collected from every layer in the network protocol stack. Figure 2.8 shows some of the handover decision parameters used by vertical handover decision algorithms.

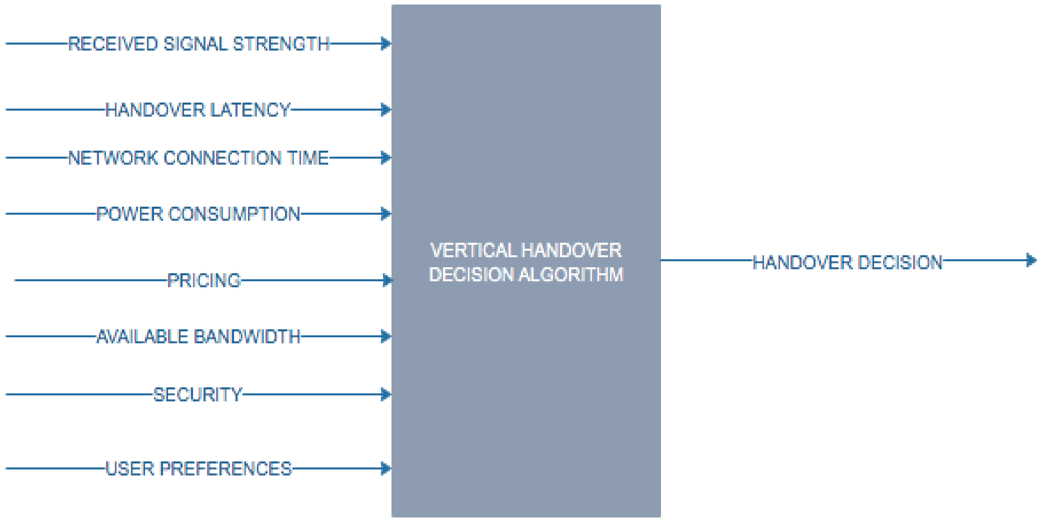


Figure 2.8: Example of parameters used by the vertical handover decision algorithm.

(6) **Handover Execution Phase -** The handover execution phase involves the seamless rerouting of connections from the source RAT to target RAT. During this phase, the target RAT may need to authenticate and authorize the MT to access new RAT's network resources.

2.4.3 Characteristics of Seamless Handover

A seamless call handover process is essential in the provisioning of guaranteed QoS and effective utilization of network resources. Below is an explanation of some of the characteristics of a seamless call handover process.

(1) **Speed** - Call handover process must be executed as fast as possible to support service continuity and avoid QoS degradation.

(2) **Number of Handovers** – VHOs in a network are expensive. Unnecessary handovers as result of the ping-pong effect result in an additional overhead to the network leading to QoS and QoE degradation.

(3) **Reliability** - The handover decision schemes must always be reliable and satisfy the users' QoS requirements with low margins of error.

(4) **Multi-Criteria** - Call handover decision schemes must be performed based on multiple decision criteria to ensure robustness and intelligent RAT selection decisions. Some of the parameters that can be aggregated and used in multi-criteria VHO decision algorithms are shown in Figure 2.8.

Figure 2.9 below summarizes the vertical handover management concept in HWN.

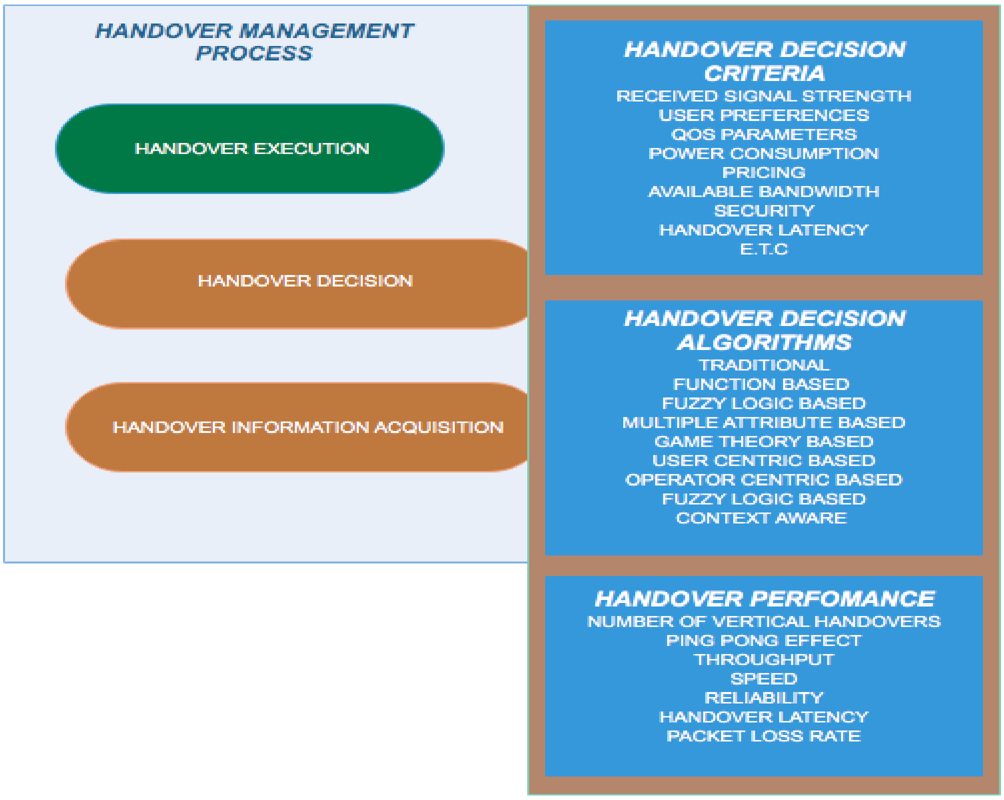


Figure 2.9: Summary of the handover management concept.

2.5 Vertical Handover decision algorithms in heterogeneous wireless networks

2.5.1 Objectives of Handovers in HWNs

Vertical handovers in HWNs involve 2 major parties, the MNOs and the end-users. Both parties have their own objectives regarding handovers, some of which possibly conflict. In this chapter, the end-user objectives and the MNO objectives will be classified as user-centric objectives and operator-centric objectives respectively. These objectives are the driving force behind the development of the existing handover decision algorithms.

User-centric Handover Objectives in Heterogeneous Wireless Networks

End-users always aim to avoid perceivable service interruptions, for example, varying resolutions during a video. The QoE perceived by the user depends on network variables such as the latency, data rates and throughput. Because of varying QoS caused by changes in network variables, a user may naturally want to switch to another RAT for an improved experience. Hence user-centric vertical handover objectives are usually satisfied from the MT, giving the user the flexibility and freedom to select the desired network based on personal preferences. The users' personal preferences include the level of QoS required for the applications, pricing, battery consumption and business payment plans with MNOs. An extensive study on user-centric objectives has been carried out in [11 - 13] and it is referred to as the *"Always Best Connected"* concept.

Operator-centric Handover Objectives in Heterogeneous Wireless Networks

There is no doubt that MNOs are mainly driven by their financial interests as they seek to maximize the revenue they generate from provisioning mobile networks to their subscribers. Like any other business entity MNOs always try to minimize their capital expenditures and operational expenses and this plays an indirect role in the MNOs' handover objectives in HWNs. MNOs also aim at simultaneously maximizing the utilization of network resources via load balancing and support seamless mobility through the use of vertical handovers. Figure 2.10 highlights some of the user-centric and operator-centric objectives for handovers in HWNs

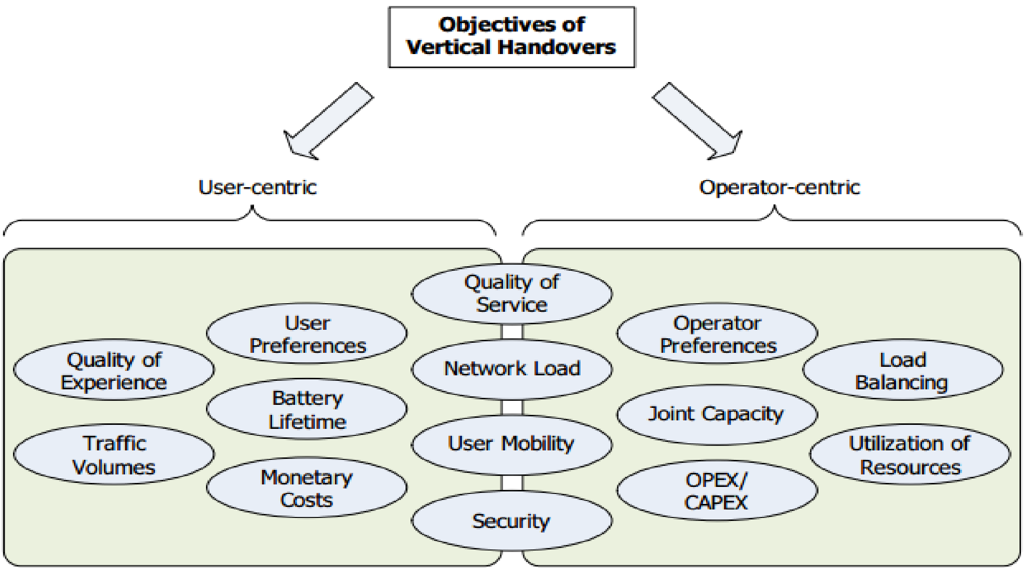


Figure 2.10: User-centric and operator-centric handover objectives [24]

The next section is an investigation and evaluation of various existing handover decision algorithms in HWNs and focus is given to some of the user-centric and operator-centric objectives of handovers [24]

2.6 Handover Decision Algorithms

VHO decision algorithms are at the core of the call handover process in HWNs. A lot of surveys [25 – 28] have successfully attempted to summarize and categorized the existing vertical handover algorithms. Authors in [25] provide an expansive list and an in-depth analysis of existing VHO decision algorithms. Based on the vertical handover objectives that need to be satisfied, different criteria may be considered for the handover decision. Varying mathematical models have been developed to handle VHO decisions in HWNs which include Markov chain-based methods, Multiple Attribute Decision-Making Algorithms (MADM), game theory, fuzzy logic utility theory, and artificial neural network-based (ANN) algorithms.

2.6.1 Multiple Attribute Decision-Making Algorithms

Multiple Attribute Decision-Making Algorithms (MADM) have been successful in selecting the best RAT from a pool of alternative candidates in HWNs. The objective of MADM algorithms is to select parameters to be used, process and normalize them and then select the best RAT from a pool of alternatives after aggregating and evaluation the weights of chosen parameters based on some multiple decision criteria.

Some of the popular MADM algorithms in literature include Multiplicative Exponent Weighting (MEW) [29], Simple Additive Weighting (SAW) [30], Gray Relational Analysis (GRA) [31], Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [32], VlseKriterijumska Optimizacija I Kompromoso (VIKOR) [33] , Analytical Hierarchy Process (AHP) [34, 36] and Elimination et Choix Traduisant la REalité (ELECTRE) [35]. Below is a discussion of some of the traditional MADM algorithms in existence.

(1) **SAW -** SAW is a simple MADM algorithm. SAW algorithm involves assigning a score to each candidate RAT by summing up the product of the attribute values and its weight and then selecting RAT that scores the highest as the best choice. SAW can be mathematically represented by Equation 2.1 [39 - 40]

$$R^*_{SAW} = argmax_{i \in M} \sum_{j=1}^{N} w_j r_{ij}$$

Equation 2.1: Saw Algorithm

Where:
i - denotes the score of each candidate RAT.
$r_{i\,j}$ - denotes the normalized contribution of each metric.
w_j - denotes the weight assigned to each metric j.
M - is the number of candidate RATs.
N – is the number of parameters.

(2) **MEW -** MEW algorithm is similar to SAW as they are both scoring MADM algorithms. MEW computes the scores of each candidate RAT by using the weighted product of the parameters considered. Using the MEW algorithm, the RAT selection problem during the VHO decision phase can be mathematically formulated as the matrix in Equation 2.2

$$R_i = \prod_{j=1}^{N} x_{ij}^{wj}$$

Equation 2.2: Mew algorithm

Where:
R_i - denotes the score of the i^{th} candidate RAT.
$x_{i\,j}$ - denotes the attribute j of the i^{th} candidate RAT.
w_j - represents the weight of attribute; $\sum_{j-1}^{N} w_j = 1$

Since the above product in Equation 2.2 does not have an upper bound, it is more reasonable to compare the score R_i with an ideal solution [39 - 40]. The selected network R^*_{MEW} is therefore given by Equation 2.3

$$R^*_{MEW} = argmax_{i \in M} R_i$$

Equation 2.3: Mew algortithm

(3) **TOPSIS** - Like SAW and MEW, TOPSIS is also a scoring MADM algorithm. In TOPSIS, the most optimal RAT is selected as the one that has a score closest to the ideal solution but furthest from the non-ideal solution. The network chosen by TOPSIS can be mathematically modelled as shown below.

$$R^*_{TOPSIS} = argmax_{i \in M} C_i$$

Equation 2.4: TOPSIS algorithm

Where:
C_i - denotes the relative similarity of the candidate i^{th} RAT to the ideal solution. [39]

(4) **AHP** - The AHP algorithm involves splitting the RAT selection problem during the VHO into smaller problems. Each small problem is then evaluated as a decision factor and AHP is then used to select the most optimal RAT from the resulting set of solutions.

Authors in [47] developed a VHO decision algorithm called Enhanced Simple Additive Weighting (E-SAW) which is an enhancement of the traditional SAW algorithm. E-SAW ranks RATs in a HWN by eliminating RATs which do not meet a minimum required QoS. E-SAW successfully improved the network's perceived QoE by mitigating the processing overhead due to unnecessary vertical handovers. However, the algorithm proposed in the paper is not tailored to make vertical handover decisions for a MT terminal that has single homing capabilities and multi-mode. This is because such MTs can only maintain a single connection with a single RAT at a time and each call originating from the MT requires different QoS provisioning.

Authors in [16] provide a comparative analysis of VHO decision algorithms which include MEW, TOPSIS, SAW, GRA, VIKOR, and ELECTRE. The performance of the above-mentioned algorithms was carried out for data and voice services in a HWN. Results showed that TOPSIS, VIKOR and SAW are best suited to make the VHO decisions for voice services due to the low packet overhead and jitter associated with voice calls. On the other hand, GRA and MEW were found to be best suited for making RAT selection decisions for services requiring high bandwidth such as data services. However, the model used by the authors is not suitable for making vertical handover decisions for a MT that is single-homed and multimode since the group of calls originating from the MT requires different QoS provisioning.

Authors in [48] proposed a context-aware VHO algorithm which is a derivative of the traditional AHP algorithm. Unlike the traditional AHP algorithm, it considers both the MT and network context for better results. However similar to [47] the algorithm is best suited to VHO decisions for a single call and did not consider decision making for multiple calls from a multimode MT with single homing capabilities.

Authors in [17] provided a VHO decision algorithm based on multi-criteria evaluation and criticality analysis. A single call was used to investigate the number of vertical handovers experienced in a HWN, the computational complexity and handover delay due to the proposed VHO algorithm. However, the algorithm proposed by the authors did not consider decision making for multiple calls from a multi-mode MT with single homing capabilities.

Falowo and Chan [7] developed a VHO decision algorithm for HWNs. The algorithm successfully solved the problem of making VHO decisions for multiple calls originating from a single-homed, multi-mode MT. The objective of the algorithm was to address the shortcomings of most of the existing vertical handover decision algorithms [16-17] [31-35] [47-48] which are not suitable for making decisions for multiple calls originating from a single-homed multimode MT. The algorithm proposed in this paper is a derivation of the TOPSIS algorithm which. The algorithm takes a user-centric approach by considering the user preferences for each RAT in the HWN.

2.6.2 Artificial Neural Network Based Algorithms

Artificial neural networks (ANNs) have recently attracted a lot of attention and this is reflected in the plethora of articles and publications available. ANN-based algorithms perform tasks by learning from past known data thus they are widely used in solving various problems ranging from pattern recognition, computer vision and machine translation among other applications.

Authors in [51] developed an ANN-based VHO decision algorithm that uses Receiver Signal Strength Indicator (RSSI) data, data rate and pricing data to make its decision. The algorithm was compared with the traditional SAW in a 5 RAT HWN consisting of Wireless Fidelity (Wi-Fi), GSM, GPRS, UMTS and Worldwide Interoperability for Microwave Access (WiMAX). The algorithm was superior to SAW in minimizing the number of unnecessary VHO as well as the handover latency.

Zineb et al [50] presented an ANN-based VHO algorithm that considers the QoS and QoE in making its decision. The VHO algorithm makes its decision based on historical data and knowledge acquired during the learning process of various QoE and QoS parameters. The algorithm succeeded in reducing the number of VHOs experienced in the network.

N. Nasser et al [52] developed an ANN-based algorithm to predict vertical and horizontal handovers in a HWN featuring of RATs supporting WLAN and GPRS. The ANN model was trained using a history of RSS values and then used pattern recognition techniques to select the most optimal RAT from a set of alternative RATs. The algorithm significantly decreased the handover latency and the number of VHOs experienced in the HWN. The downside of this scheme is the long overhead incurred during the training of the model.

Other techniques which include game theory, fuzzy logic, and utility theory have also been developed to solve the handover decision problem in HWNs. However, the algorithms have many drawbacks when compared to the above-mentioned MADM and ANN-based handover decision algorithms when selecting the best RAT in HWNs [53 -56].

2.6.3 Call history-based Algorithms

Efforts have been made to predict user call patterns in mobile wireless networks [57 -58]. Such algorithms assume that users follow regular call patterns in a network. History-based algorithms require sufficiently large datasets to be collected before predictions are made with reasonable accuracy. The vertical handover decision can then be made by employing an ANN-based algorithm or Markov Chain models.

Authors in [2] have proposed a call history-based vertical handover decision algorithm to make the initial RAT selection decision in HWNs. The proposed scheme was successful in reducing the frequency of VHOs in HWNs. However, the scheme like any other history-based predictive scheme requires large datasets for algorithm beforehand to infer from. The algorithm is based on the fact that each user follows recurring call patterns and as a result, it may give inaccurate results if there are recent changes in the user's call patterns.

In this study, a predictive call history-based algorithm that is suitable to make handover decisions for a single-homed, multi-mode MT in HWNs is proposed.

Chapter 3 : Modeling

In this chapter, a model to evaluate the call dynamics of a multi-mode MT within a HWN environment is first presented. The model presented in this section follows the one given by *O.E Falowo et al* [46].

3.1 Modelling the call dynamics of a multi-mode mobile terminal

To clearly define the multi-mode MT considered in the modeling of the call dynamics in this study consider the following example.

Example 1

Luiz is chatting with his friend Granit on a *voice* call and at the same time downloading a music album on Apple Music in the background. Granit asks Luiz to check out his video on his YouTube channel and provide him some feedback. In this scenario, Luiz ends up simultaneously using *voice, data* and *video* services simultaneously.

Luiz's multi-mode MT supports voice, data and video services and can form parallel connections running any combination of calls at the same time. However, the MT's parallel connections are restricted to only a single RAT at a time. Figure 3.1 illustrates is a state transition diagram of the described multi-mode MT. All the possible states of the MT can be derived from the state transition diagram and are shown in Table 3.2. Using Table 3.2., a first-order Markov Chain illustrating the call dynamics of the multi-mode MT can be developed.

Markov chain model of Call Dynamics of a Multi-mode mobile terminal

Consider a first-order Markov chain$\{ X_n\}_{n=0}^{\infty}$, where $S = \{ S_0,\ S_1,\ S_2,\ S_3, S_4, S_5\ , S_6, S_7\}$ is a set of all the its possible states and Let S_i denote a multi-mode MT in state i. Let n be any time interval during which the multi-mode MT can be in any state $S_i\ \in\ S$. The probabilities of MT transitioning from one state to another are given in Equation 3.1 [46]. Let $p_{i,j}$ denote the probability of the multi-mode MT transitioning from S_i to S_j.

$$P = \begin{pmatrix} p_{0,0} & \cdots & p_{1,7} \\ \vdots & \ddots & \vdots \\ p_{7,0} & \cdots & p_{7,7} \end{pmatrix}$$

$$\sum_{x=0}^{7} P_x = 1$$

$$\forall i\ \in S\ and\ \ 0 \leq P_{i,j} \leq\ 1$$

Equation 3.1: Probability Transition Matrix of the Markov Chain for multi-mode MT

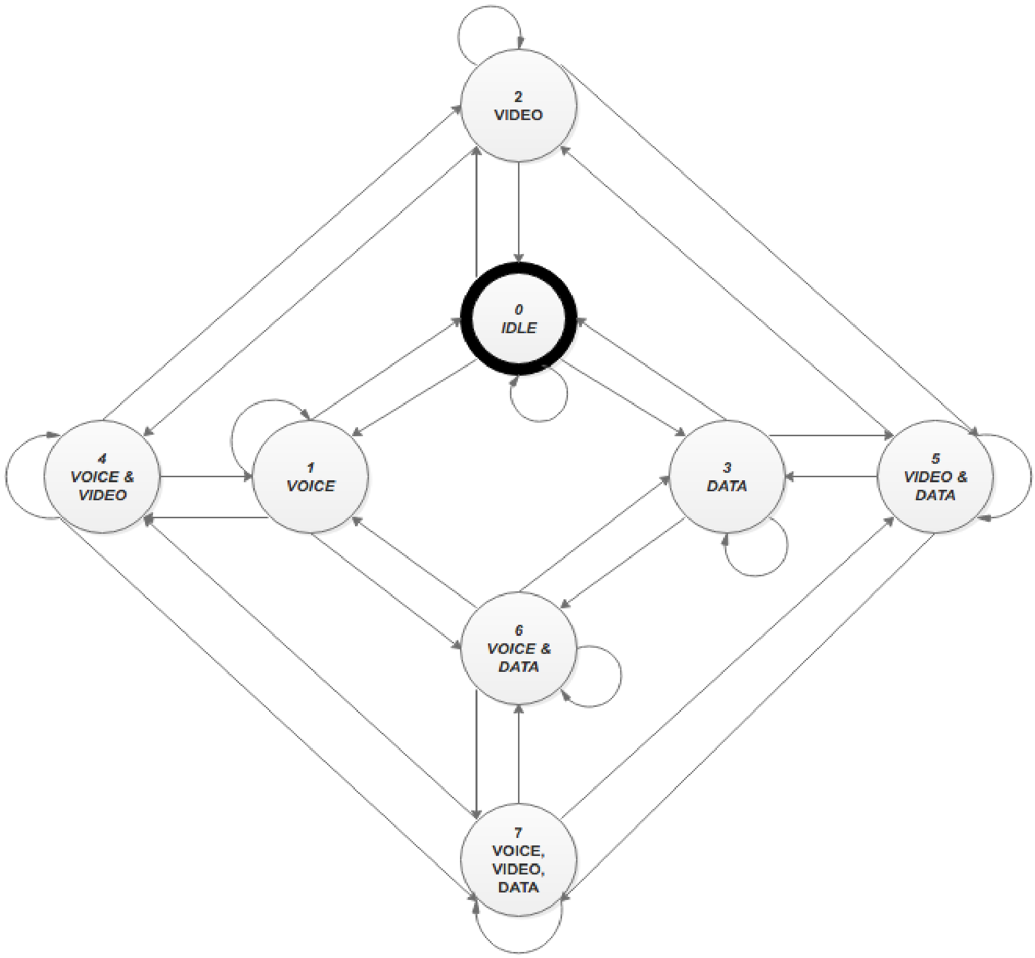


Figure 3.1: State Transition Diagram of multi-mode MT supporting 3 services.

Table 3.1: Call dynamics of a multi-mode MT supporting 3 services. [2]

State	Class of calls
0	Idle **(no ongoing call)**
1	Voice only
2	Video only
3	Data only
4	Voice and Video
5	Video and Data
6	Voice and Data
7	Voice, Video and Data

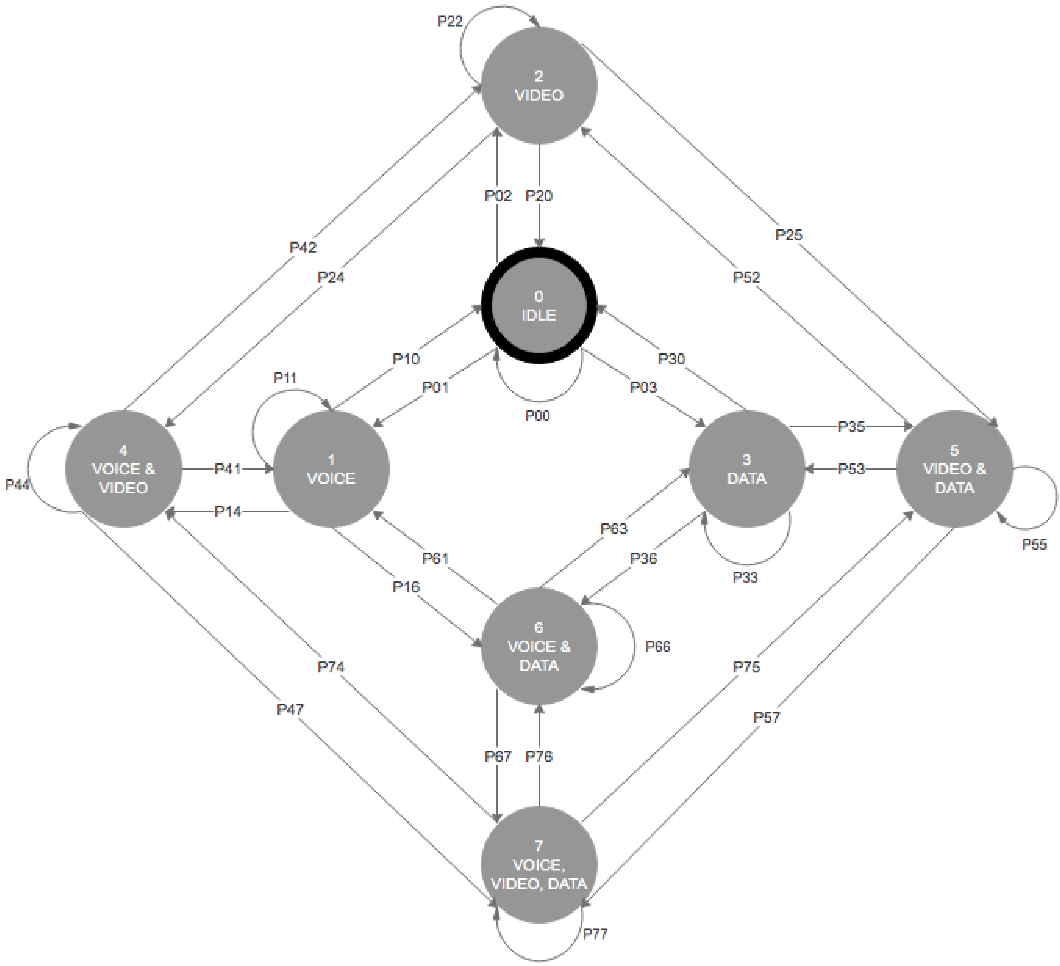


Figure 3.2: Markov Chain of the call dynamics of a multi-mode MT supporting 3 services.

3.2 Heterogeneous Wireless Network Model

The HWN model used in this paper is similar to the one developed by O.E Falowo et al [46] where R denotes the set all the RATs in the HWN and M denotes a set of all the services supported in the HWN such that

$R = \{ R_1, \ldots\ldots, R_{|R|} \}$ where $| R |$ is the number of RATs in the network and

$M = \{ M_1, \ldots\ldots, M_{|M|} \}$ where $| M |$ is the number of services supported in the HWN

Each RAT is capable of supporting $| M |$ services or | N | services where $N \subset M$. The capacity of each RAT in the HWN is represented as C_i where C_i denotes the capacity of R_i. Each class of call in the HWN requires different network resources, measured in basic bandwidth units (bbu). Thus, we can define a set $B = \{ B_0, B_1, B_2, B_3, B_4, B_5, B_6, B_7 \}$ where B_i denotes the bbu requirements of a multi-mode MT is state $S_i \in S$. In this study a HWN model shown in Figure 3.3 is considered. The arrows in Figure 3.3 illustrate only the necessary VHOs and a detailed explanation is given in Chapter 4.

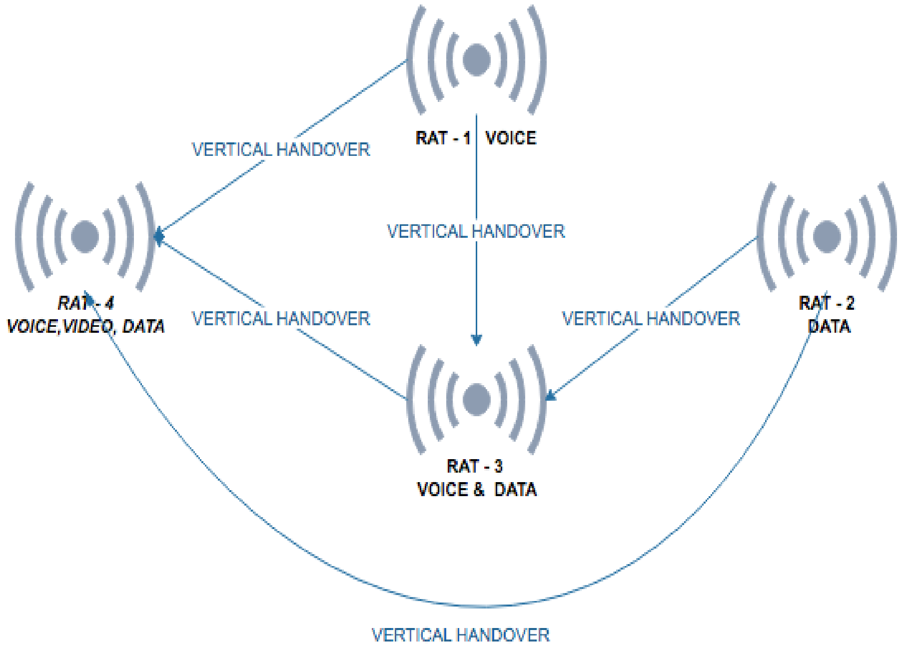


Figure 3.3: Four RAT heterogeneous wireless network model

3.3 Call Dynamics of a multimode MT in a Heterogeneous Wireless Network

Consider the multimode MT defined in Chapter 3.1 and the HWN model shown in Figure 3.3. If the MT changes its state from S_i to S_j where $S_i, S_j \in S$ and $j > i$, and serving RAT cannot support MT in state S_j a VHO to another RAT may be necessary, if possible. Thus a relationship between VHOs in and the call dynamics of a multi-mode MT in HWNs can be established. A relationship between the frequency of VHOs and a call dynamics of a multi-mode MT can also be established since it determines the RAT the MT can establish a connection with at any given time. In Chapter 2 minimizing the number of VHOs was discussed as one of the characteristics of a seamless VHO. Below are some of the advantages of minimizing VHOs in HWNs. [46]

(1) Increase in speed of vertical handovers through reduction of vertical handover overhead
(2) Reduction in battery consumption of a multimode MT
(3) Effective utilization of network radio resources
(4) Improved QoS requirements and perceived QoE

Chapter 4 : Predictive Algorithm Design

In this Section, the basic principle of the proposed call history-based VHO algorithm is developed.

4.1 Development of the Call History-Based Predictive Algorithm

Consider the multi-mode MT in Chapter 3 and the HWN model given in Figure 3.3. Define a call session $< K >$ as a sequence of MT states starting when MT is idle, S_0 and terminating when the MT is back to idle state again S_0 but has at least one state other than S_0 in the sequence. To clearly define the session $< K >$, consider the following examples:

Example 2

Consider Jessie using a multi-mode MT in the HWN. At 10.30 am Jessie's MT was switched off, thus state S_0. At 10:35 am he decides to call his friend Granit, hence mobile terminal transitions to S_1. After a 10-minute conversation, Alexis ends the call at 10:45 am, hence MT transitions back to idle state, S_0. Figure 4.1 depicts Jessie's call session.

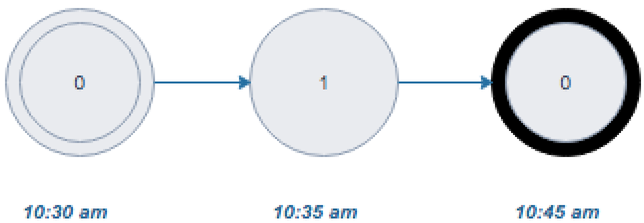


Figure 4.1: Call session described in example 2.

Example 3

Consider another user Rashford using a multimode MT in the HWN. Rashford was not on any ongoing call at 6:00 pm thus his MT was in idle state S_0. At 6.01 pm Rashford started downloading a music album, thus MT transitions to state S_3 signifying a data call only. At 6.30 pm Rashford receives a call from Jessie his classmate, thus a transition of MT to state S_6 signifying voice and data calls. During his call with Jessie, at 6.35 pm Rashford's album download finishes and he receives a push notification from iTunes App, hence MT transitions to state S_1, voice-only call. At 7:00 pm Rashford ends his conversation with Jessie, thus MT transitions back to the idle state, S_0. Figure 4.2 illustrates Rashford's call session.

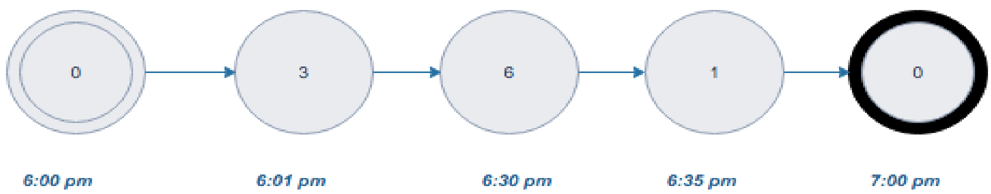


Figure 4.2: Call session described in example 3.

It is important to note that Rashford's initial call represented by a state transition S_0 to S_3 is supported by RATs R_2, R_3 and R_4. Assuming that R_2, R_3 and R_4 have enough available capacity to admit Rashford's call, consider the following cases:

(1) **Initial call admitted into $\boldsymbol{R_2}$**- When MT transitions to state S_6 from state S_3 a necessary vertical handover to R_3 will be required as shown in Figure 3.3. It is evident that any scheme that is able to anticipate the state S_6 and allows the initial call to be admitted into R_3 can minimize the number of vertical handovers by avoiding the necessary vertical handover required for state transition from S_3 to S_6.

(2) **Initial call admitted into $\boldsymbol{R_4}$** - By admitting the MT into R_4 the necessary vertical handover that must occur when the multimode MT transitions to S_6 from S_3 can also be avoided. However, this is not the optimal decision as it is more intelligible from the HWN's perspective to reserve R_4 network resources for video call users. In this context R_3 becomes the optimal choice.

(3) **$\boldsymbol{R_3}$ does not have enough network resources but $\boldsymbol{R_1}$ and $\boldsymbol{R_4}$ have enough network resources** - In this case, the most optimal decision is to admit the initial call into R_4. By this the necessary vertical handover when the multimode MT transitions to S_6 from S_3 can also be avoided however at the expense of video call users. Admitting the call into RAT R_2 does not give us any performance gain as necessary handover due to state transition to S_6 from S_3 is still executed. Therefore, the most optimal decision, in this case, depends on the demand load on R_4. If R_4 is heavily loaded the most optimal decision is to admit call into R_2 and reserve resources for video calls in R_4 and if R_4 is lightly loaded the most optimal choice is to admit call into R_4 hence gain the advantages of minimizing the number of vertical handovers.

The discussion above forms the foundation from which the proposed predictive VHO algorithm is built on. The main objective of the algorithm is to predict the next state of the multi-mode MT when the user initiates a new call which marks the start of a new session hence minimize the frequency of unnecessary VHOs and give priority to handover calls.

4.2 User Call History

In the proposed VHO predictive algorithm, the MT stores a history of all its call sessions. The initiation of a new call session triggers the algorithm to retrieve and analyze the user's call logs. The algorithm computes and populates the probability transition matrix P given in Equation 3.1 using methods given in Chapter 4.3. Figure 4.3 is an extract of call history stored on a user's MT.

Below is a description of the fields found in a user's call history

(1) ***UserId*** - To uniquely identify a user.
(2) ***SessionId*** - To uniquely identify the user's call session
(3) ***StartTime*** - To record the starting time of each call session
(4) ***Duration*** - To record the duration of a session
(5) ***Session Sequence*** - A sequence of all the state changes during the session

UserId	SessionId	StartTime	Duration	SessionSequence
9e78e7af-6b1a-426b-b05d-37748d3964eb	40e48527-8842-4dc2-82ba-068d40b89f86	09/10/2019 12:38:36	00:08:39.0389430	01630
9e78e7af-6b1a-426b-b05d-37748d3964eb	edb016eb-2835-415c-94f3-476a0ae45f34	09/10/2019 12:49:03	00:45:02.6725240	01630
9e78e7af-6b1a-426b-b05d-37748d3964eb	fc2ae4d9-38f6-42a2-a052-f544db084daf	09/10/2019 13:41:16	00:21:39.7620000	03530
9e78e7af-6b1a-426b-b05d-37748d3964eb	7b5f302c-9afb-4475-9853-20e130d3b205	09/10/2019 15:33:08	00:05:59.6590000	010
9e78e7af-6b1a-426b-b05d-37748d3964eb	905be551-ba64-4eee-92dc-4bae4dc11bca	09/10/2019 16:41:16	00:21:39.7620000	020
9e78e7af-6b1a-426b-b05d-37748d3964eb	ebd948f7-3ffe-40b0-a602-0a341d59e689	09/10/2019 17:33:08	00:05:59.6590000	03530
9e78e7af-6b1a-426b-b05d-37748d3964eb	98789afc-ce98-4037-b2f0-9a7bc2edc156	09/10/2019 17:55:16	00:21:39.7620000	0252410
9e78e7af-6b1a-426b-b05d-37748d3964eb	5b2bcd8a-303b-4f59-bf53-673f687b7a34	09/10/2019 19:33:08	00:25:59.6590000	03530
9e78e7af-6b1a-426b-b05d-37748d3964eb	e8451562-b69b-4064-bb1a-0194c74076d5	10/10/2019 12:41:39	00:16:37.7832910	030
9e78e7af-6b1a-426b-b05d-37748d3964eb	8ec88765-8124-40c3-9405-6d15b4b5ffe0	10/10/2019 13:07:02	00:08:04.2010000	03630
9e78e7af-6b1a-426b-b05d-37748d3964eb	ed035453-e042-4440-9480-e9c5ea5ae2d0	10/10/2019 13:15:35	00:21:45.0700000	03630
9e78e7af-6b1a-426b-b05d-37748d3964eb	d3e4311f-3fe4-4680-a5fd-ba3019422efc	10/10/2019 15:41:39	00:16:37.7832910	01630
9e78e7af-6b1a-426b-b05d-37748d3964eb	3fc80a22-329d-41ca-a59b-f7dd5f264de5	10/10/2019 16:07:02	00:08:04.2010000	03630
9e78e7af-6b1a-426b-b05d-37748d3964eb	9bdf19bb-e1e3-45c8-84b4-00b41ed2107c	10/10/2019 19:15:35	00:21:45.0700000	03630
9e78e7af-6b1a-426b-b05d-37748d3964eb	830cbcbb-06d3-4297-88e5-583aebd84c6b	10/10/2019 20:41:39	00:16:37.7832910	0252410

Figure 4.3: Extract of the user's call history log database.

4.3 Vertical Handover prediction process

Consider a user about to initiate a new call with MT in state S_0 . Starting a call from this MT will mark the start of a new call session <K> and result in the MT transitioning from S_0 to some other state $S_j \in \{ S_1, S_2, S_3 \}$. The proposed predictive VHO algorithm only focuses on predicting the state S_j when a new call that marks the start a session is initiated as shown in Figure 4.4 The same principle can be extended to predict further steps ahead.

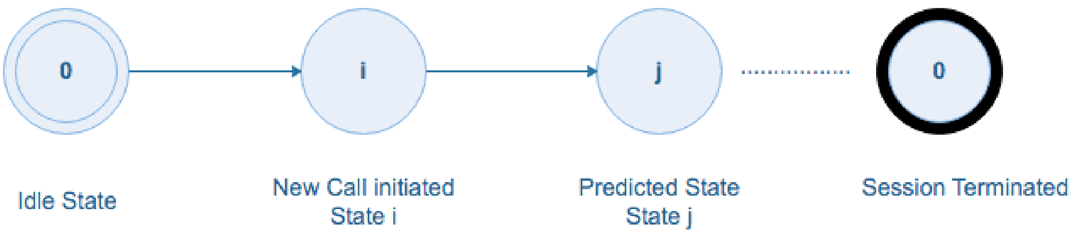


Figure 4.4: Illustration of the vertical handover prediction process.

4.4 RAT Selection

Consider the extract of user's call history provided in Figure 4.3 belonging to a user with a MT in idle state S_0. After some time, the user starts a data, thus a MT state transition from S_0 to S_3 is triggered.

Let $n_{i,j}$ denote the frequency of the MT state transitions from S_i to S_j in all the sessions of the user's call history. An entry in the probability transition matrix $p_{i,j}$ in Equation 3.1 is computed using Equation 4.1 below.

$$p_{i,j} = \frac{n_{i,j}}{\sum_{j \in S, i \neq j} n_{i,j}}$$

Equation 4.1: Computation of the probability transition matrix

Using the user's call history logs in Figure 4.3 we can compute the probability of user transitioning from S_3 to S_5 as shown below

$$p_{3,5} = \frac{p_{3,5}}{p_{3,0} + p_{3,5} + p_{3,6}} = 0.375$$

It is not necessary to compute all the entries of the probability transition matrix P in Equation 4.1 thus the computational load of the algorithm is reduced. Figure 4.5 shows a summary of only the necessary entries of the probability transition matrix for the user.

State i	State j	Frequency	Probability
1	0	1	0.250
1	4	0	0.000
1	6	3	0.750
2	0	1	0.300
2	4	0	0.000
2	5	2	0.700
3	0	1	0.125
3	5	3	0.375
3	6	4	0.500

Figure 4.5: Probability analysis of users' call history.

Figure 4.5 shows that $p_{3,0} = 0.125$, $p_{3,5} = 0.375$ and $p_{3,6} = 0.125$. **Error! Reference source not found.** shows the possible next state values after initiating a data call and the final handover decision. In this case, the MT is highly likely to transition into S_5 . The algorithm selects R_4 as the most optimal RAT since it can support MT in the predicted state S_5. If of a non-predictive scheme is employed and a decision is made on either R_2 or R_3, a necessary VHO would be eventually required in the event that the user goes on and initiates a video call (which pushes MT into S_5). Thus the VHO prediction algorithm minimizes the number of VHOs for multi-mode MTs in HWNs.

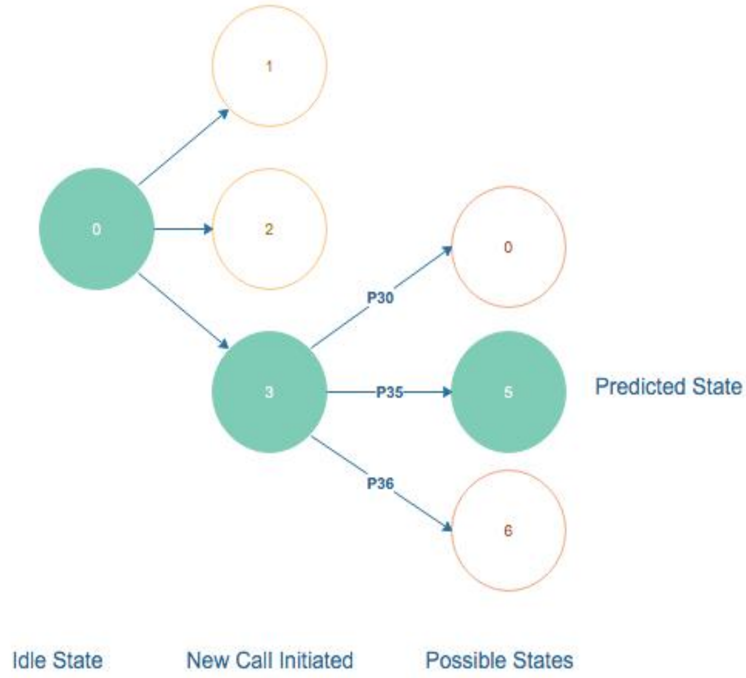


Figure 4.6: Example of a vertical handover decision using predictive algorithm.

4.5 Dealing Equally Probable Predictions and Close Predictions

The proposed call history-based one-step forward predictive algorithm may give rise to cases where there are two or more next state probabilities that are equal or very close to each other. To deal with this case a prediction threshold T_{pred} is set such that if the difference between the probabilities of the highest probable states $|p_{i_1j_1} - p_{i_2j_2}| \leq T_{pred}$ then a RAT that supports both predicted states is selected as shown in Figure 4.7. Assuming $T_{pred} = 0.01$, $p_{3,0} = 0.125$, $p_{3,5} = 0.43756$ and $p_{3,6} = 0.4374$, $|p_{3,5} - p_{3,6}| < T_{pred}$ hence a RAT that supports MT in states S_5 and S_6 is selected by the algorithm.

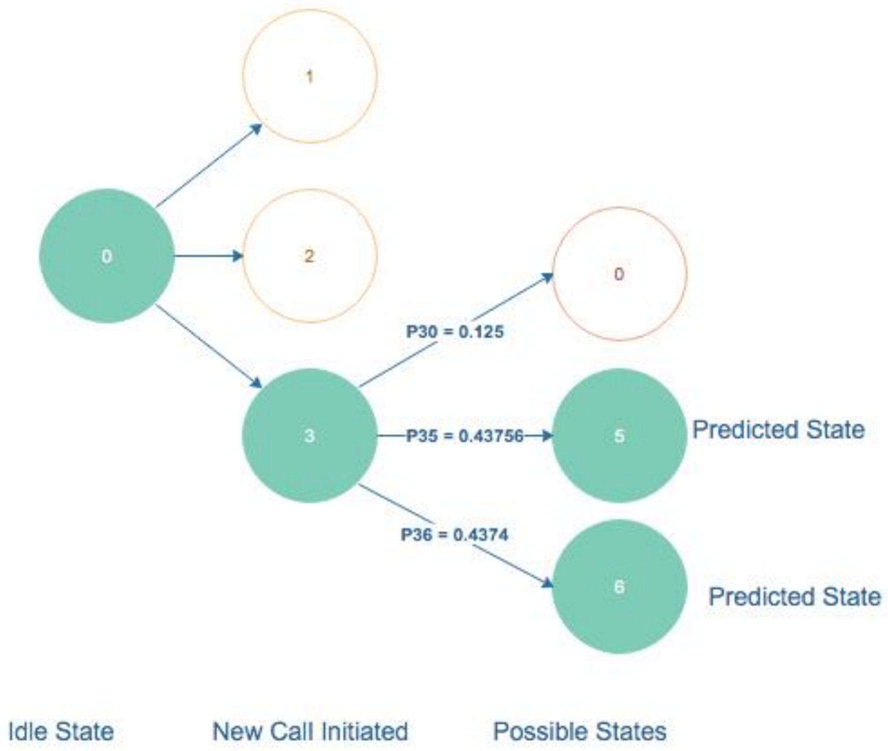


Figure 4.7: Illustration of RAT selection decision for equal and close next state predictions.

4.6 Proposed call history-based predictive algorithm

Flowchart of the proposed Algorithm

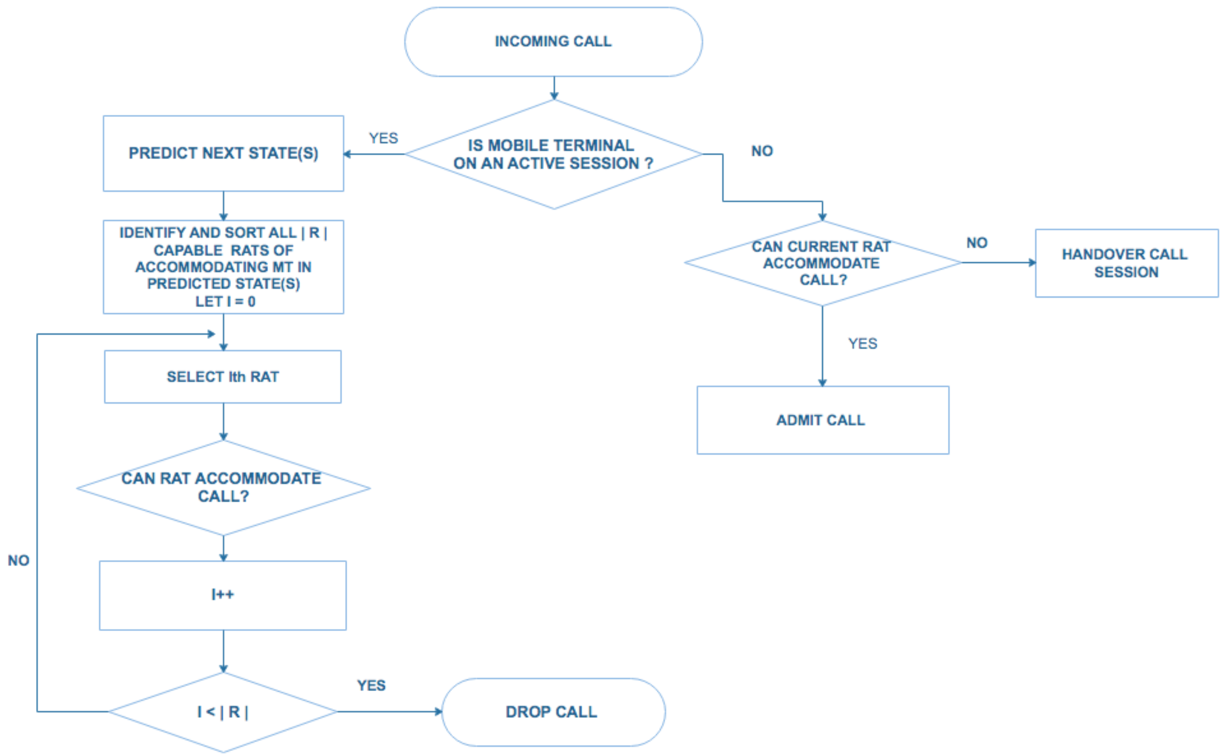


Figure 4.8: Flowchart of the proposed predictive vertical handover algorithm.

Chapter 5 : Design Tools and Implementation of Proposed Predictive Algorithm

This chapter details the implementation of the proposed call history-based vertical handover prediction algorithm. The choice of development environment was chosen to be Dotnet Core 3.0 using C# language due to its simplicity in modelling the network environment to test the algorithm. A desktop user interface was also developed using a cross-platform user interface framework called Electron. A CSV file was used to emulate a database of user call history and is loaded in memory at application start-up.

5.1 System Requirements for running Application

To run the standalone simulation tool you require

(1) A computer running Windows 10 64-bit or macOS High Sierra 64 bit or later versions.

Figure 5.0 is a screenshot of the simulation tool. See APPENDIX A for the installation guide and instructions to use the tool.

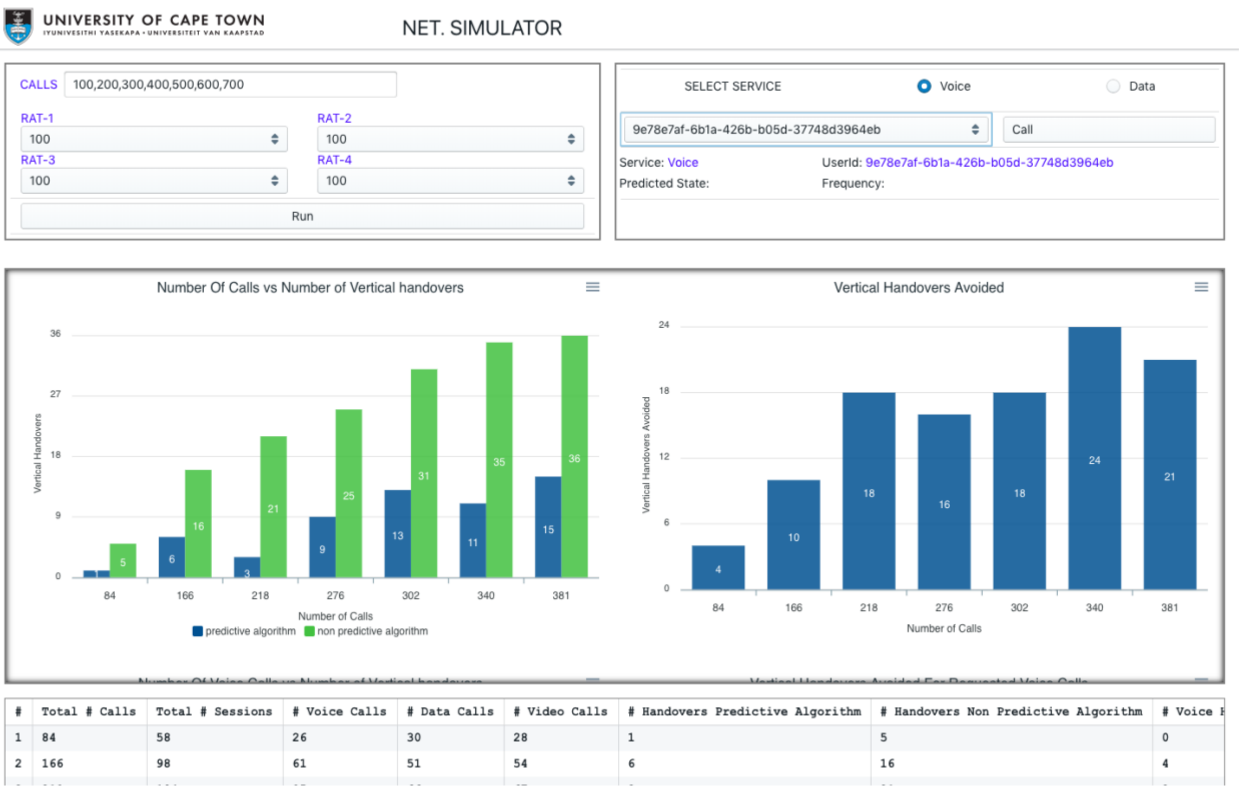


Figure 5.1: Screenshot of the simulation tool.

An Object-Oriented approach was taken to model all the network components necessary to simulate the call dynamics of a multimode MT in a HWN as well as evaluate the performance of the proposed algorithm. Below is a discussion of the implementation of the algorithm and modules that make up the simulation tool. See APPENDIX B for the source code.

5.2 CallSession Module

The CallSession module contains objects to model a call, user call session and types of services supported in the HWN.

5.1.1 Service Enumeration

The Service enumeration models the types of services supported in the HWN. Figure 5.2 shows the UML class diagram of the Service enumeration and Figure 5.3 shows its C# implementation.

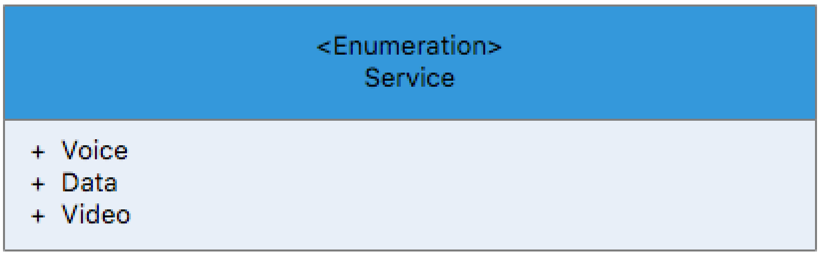


Figure 5.2: UML class diagram of the Service enumeration.

```
namespace VerticalHandoverPrediction.CallSession
{
    public enum Service
    {
        Voice,
        Data,
        Video,
    }
}
```

Figure 5.3: C# implementation of the Service enumeration.

5.1.2 Call Object

The Call class models a user's call in a HWN. A Call object is created every time a new call is initiated and below is a description the properties that make up the call object.

(1) **CallId**: Unique identifier of each call.
(2) **MobileTerminalId**: Unique identifier of each MT user.
(3) **Service**: The type of service call initiated.
(4) **StartTime**: Starting time of a call.
(5) **EndTime**: Time when a call is terminated. This property is updated whenever associated call is terminated.

Figure 5.4 illustrates the UML class diagram of the Call class and Figure 5.5 shows C# code of the interface implemented by the Call class.

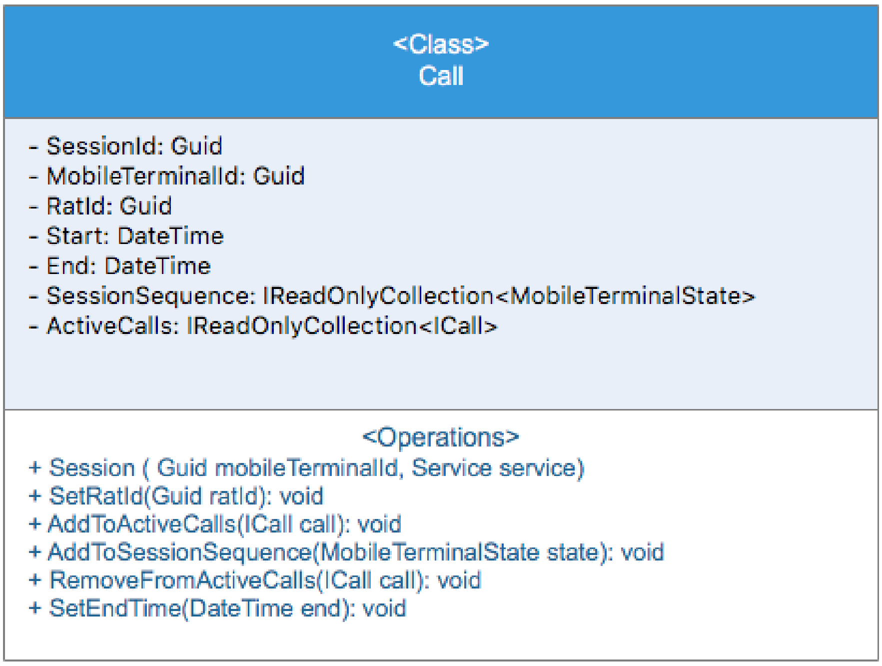


Figure 5.4: UML class diagram of the Call class.

```
namespace VerticalHandoverPrediction.CallSession
{
    using System;
    public interface ICall
    {
        Guid CallId { get; }
        Guid MobileTerminalId { get; }
        Service Service { get; }
        DateTime StartTime { get; }
        DateTime EndTime { get; }
    }
}
```

Figure 5.5: C# interface implemented by the Call class.

5.1.3 Session Object

The Session object represents a user's call session in the HWN. A session object is created every time a new session is started by a user. Figure 5.6 illustrates the UML class diagram of the Session class and Figure 5.7 shows C# code of the interface implemented by the Session class.

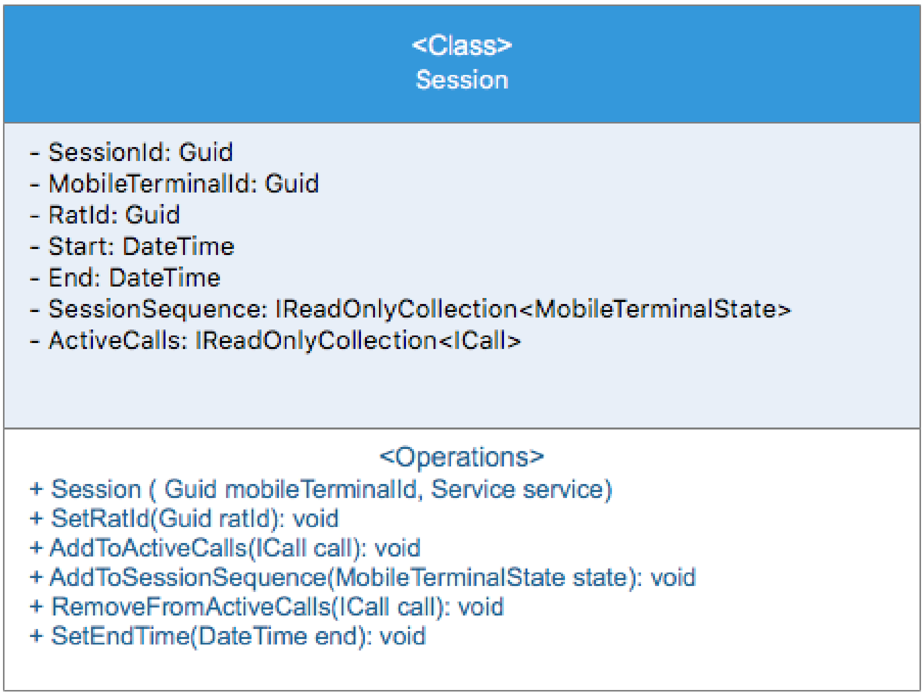


Figure 5.6: UML class diagram of the Session class.

```
namespace VerticalHandoverPrediction.CallSession
{
    using System;
    using System.Collections.Generic;
    using VerticalHandoverPrediction.Mobile;

    public interface ISession
    {
        Guid SessionId { get; }
        Guid RatId { get; }
        DateTime Start { get; }
        DateTime End { get; }
        IReadOnlyCollection<MobileTerminalState> SessionSequence { get; }
        IReadOnlyCollection<ICall> ActiveCalls { get; }

        void AddToActiveCalls(ICall call);
        void AddToSessionSequence(MobileTerminalState state);
        void RemoveFromActiveCalls(ICall call);
        void RemoveFromSessionSequence(MobileTerminalState state);
        void SetEndTime(DateTime end);
        void SetRatId(Guid ratId);
    }
}
```

Figure 5.7: C# Interface implemented by the Session class.

Below is a description of the properties and operations contained in the Call class.

(1) **SetRatId**(*Guid ratId*) - Sets the RAT Id on which the session is admitted.
(2) **SessionId** - Unique identifier of each user's call session.
(3) **RatId** - Unique identifier of the RAT on which an active session is admitted.
(4) **Start** - Time the session is initiated.
(5) **End** - Time the session is terminated. Updated when a session is terminated.

(6) **ActiveCalls** – Keeps track of all the active calls in a user's call session.
(7) **AddToActiveCalls**(*ICall call*) - Adds call to an ongoing session
(8) **AddToSessionSequence**(*MobileTerminalState state*) - Update the session sequence with MT state. This is stored in call history once session is terminated
(9) **RemoveFromActiveCalls**(*ICall call*) - Removes call from list of active calls when call is terminated.
(10) **SetEndTime**(*DateTime end*) - Sets the end time of the session once its terminated.
(10) **SessionSequence** – List to store the MT state changes during a user's call session.

5.2 MobileTerminal Module

The MobileTerminal module contains objects to model a user's MT in a HWN as described in Chapter 3.

5.2.1 MobileTerminalState Enumeration

The MobileTerminalState Enumeration represents all the 8 possible states of a MT described in Table 3.1 as an Enumeration.

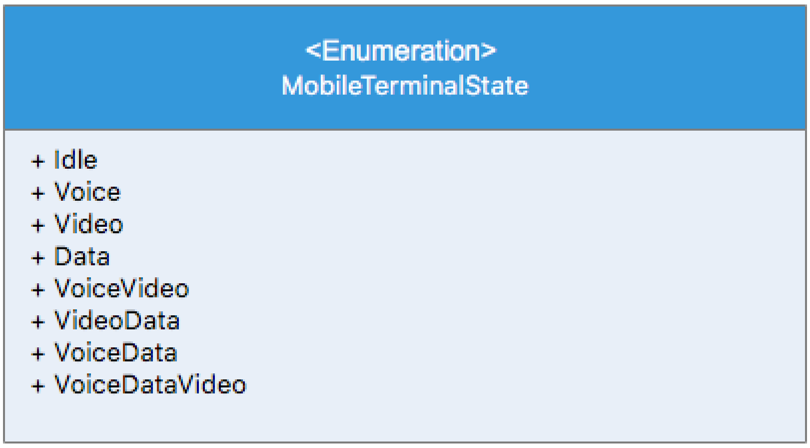


Figure 5.8: UML class diagram of the MobileTerminalState enumeration.

```
namespace VerticalHandoverPrediction.Mobile
{
    public enum MobileTerminalState
    {
        Idle,
        Voice,
        Video,
        Data,
        VoiceVideo,
        VideoData,
        VoiceData,
        VoiceDataVideo,
    }
}
```

Figure 5.9: C# implementation of the MobileTerminalState enumeration.

5.2.2 MobileTerminal Object

The MobileTerminal object models a single-homed multimode MT.

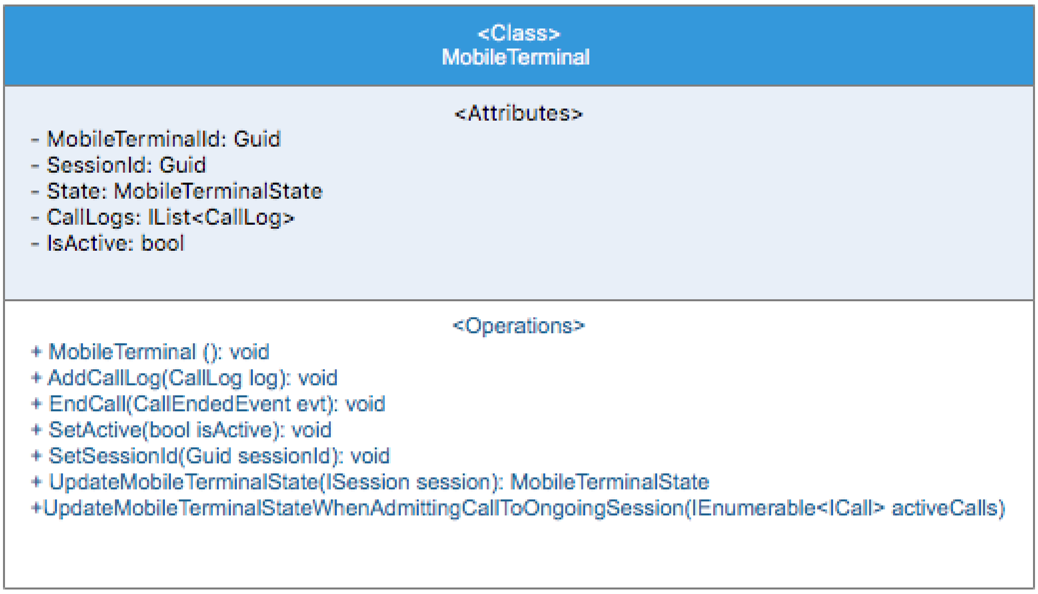
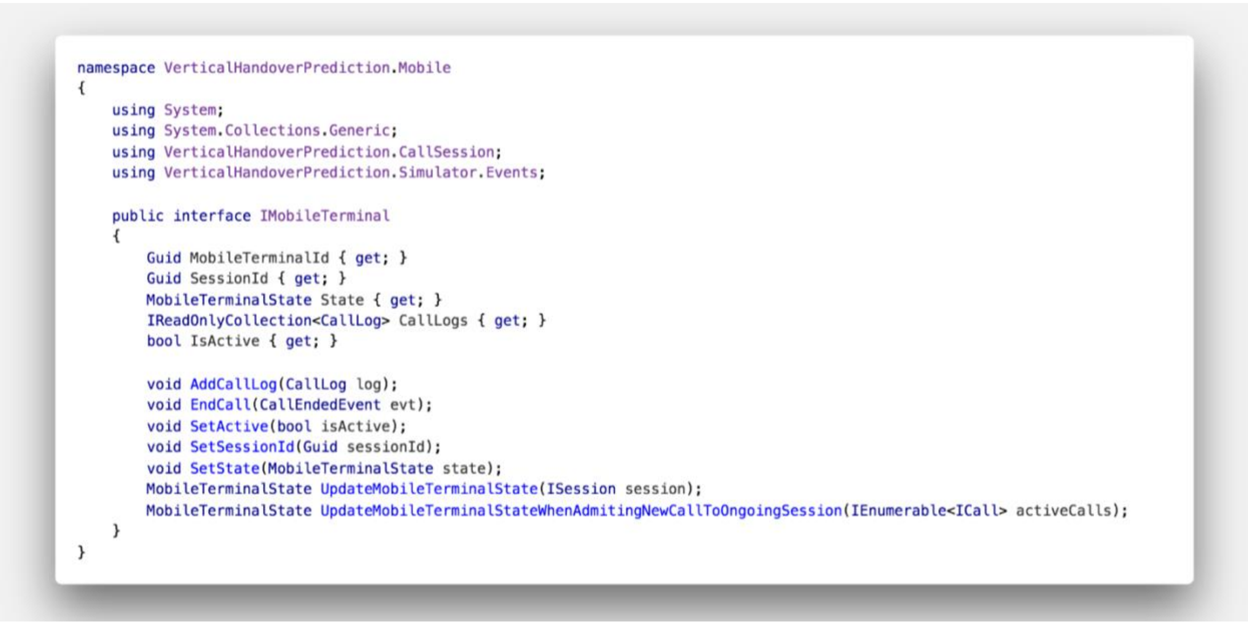


Figure 5.10: UML class diagram of the MobileTerminal class.



```
namespace VerticalHandoverPrediction.Mobile
{
    using System;
    using System.Collections.Generic;
    using VerticalHandoverPrediction.CallSession;
    using VerticalHandoverPrediction.Simulator.Events;

    public interface IMobileTerminal
    {
        Guid MobileTerminalId { get; }
        Guid SessionId { get; }
        MobileTerminalState State { get; }
        IReadOnlyCollection<CallLog> CallLogs { get; }
        bool IsActive { get; }

        void AddCallLog(CallLog log);
        void EndCall(CallEndedEvent evt);
        void SetActive(bool isActive);
        void SetSessionId(Guid sessionId);
        void SetState(MobileTerminalState state);
        MobileTerminalState UpdateMobileTerminalState(ISession session);
        MobileTerminalState UpdateMobileTerminalStateWhenAdmitingNewCallToOngoingSession(IEnumerable<ICall> activeCalls);
    }
}
```

Figure 5.11: C# interface implemented by the MobileTerminal class.

Below is a description of all the properties and operations of the MobileTerminal object.

1. **MobileTerminalId***:* Unique identifier of a MT in the HWN.
2. **SessionId**: Holds the reference to the MT's current session.
3. **MobileTerminalState**: Holds the current state of the MT.
4. **CallLogs**: Represents the list of the MT's call log history used for prediction. Once a session is terminated the terminate session is persisted to the database.
5. **IsActive**: Flag is essential in tracking whether or not the MT is in on an active/ongoing session

6. **AddCallLog***(CallLog log)*: Adds log of terminated session to the users call log history
7. **EndCall***(CallEndedEvent evt)*: Used to terminate a call. The CallEndedEvent object passed in as a parameter consists of the CallId of the call in question.
8. ***SetActive****(bool isActive)*: Mutates the IsActive flag on the MT object.
9. **SetState***(MobileTerminalState state)*: Mutates the state of the MT.
10. **UpdateMobileTerminalState***(ISession session)*: Used to update the MT to its current state when a new session is started and returns the updated state
11. **UpdateMobileTerminalStateWhenAdmittingNewCallToAnOngoingSession***(IEnumerable<ICall> activeCalls)* : Used to update the current state of the MT when a MT transitions to another state during an ongoing session and returns the updated state

5.2.3 CallLog Object

The CallLog object represents properties that are persisted to the data store once a user session is completed.

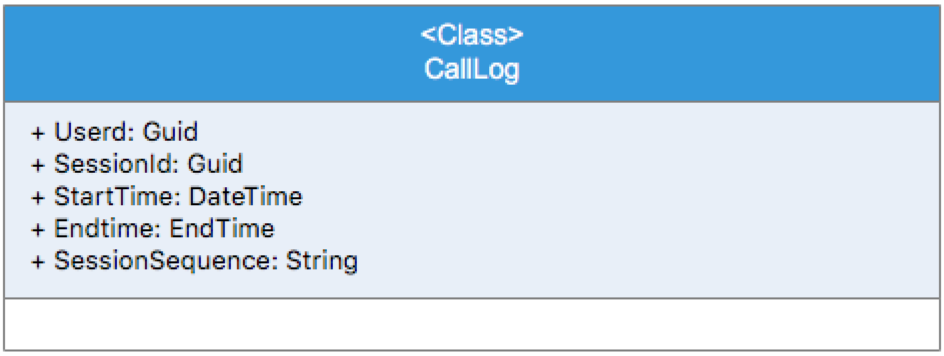


Figure 5.12: UML class diagram of the CallLog class.

```
namespace VerticalHandoverPrediction.Mobile
{
    using System;
    using CsvHelper.Configuration;

    public class CallLog
    {
        public Guid UserId { get; set; }
        public Guid SessionId { get; set; }
        public DateTime StartTime { get; set; }
        public TimeSpan Duration { get; set; }
        public string SessionSequence { get; set; }
    }

    public class CallLogMap: ClassMap<CallLog>
    {
        public CallLogMap() => AutoMap();
    }
}
```

Figure 5.13: C# implementation of the CallLog class.

Below is a description of the properties found in the CallLog class
(1) **UserId**: Unique identifier of the MT.
(2) **SessionId**: Unique identifier of the session.
(3) **StartTime**: Represents the starting time of associated session.

(4) **Duration**: Stores the duration of the session
(5) **SessionSequence**: Stores all the state changes of MT during a user's call session.
(6) **CallLogMap: ClassMap<**CallLog**>** : Helper Class to help map the CallLog object to a csv file (database)

5.3 Network Module

The Network module contains objects that model all the components and parameters of the HWN described in Chapter 3. The Network module contains two classes a RAT class to model a RAT and a HetNet class to model a HWN. See Appendix B for full implementation details of the module.

5.3.1 HetNet Object

The HetNet class is implemented as a singleton class and it consists of properties and operations used to model the 4 RAT HWN described in Chapter 3. The HetNet Object also has the responsibility of keeping track of all the network parameters of interest during simulation. Figure 5.14 illustrates the UML class diagram of the HetNet class and Figure 5.15 shows the C# interface implemented by the HetNet class.

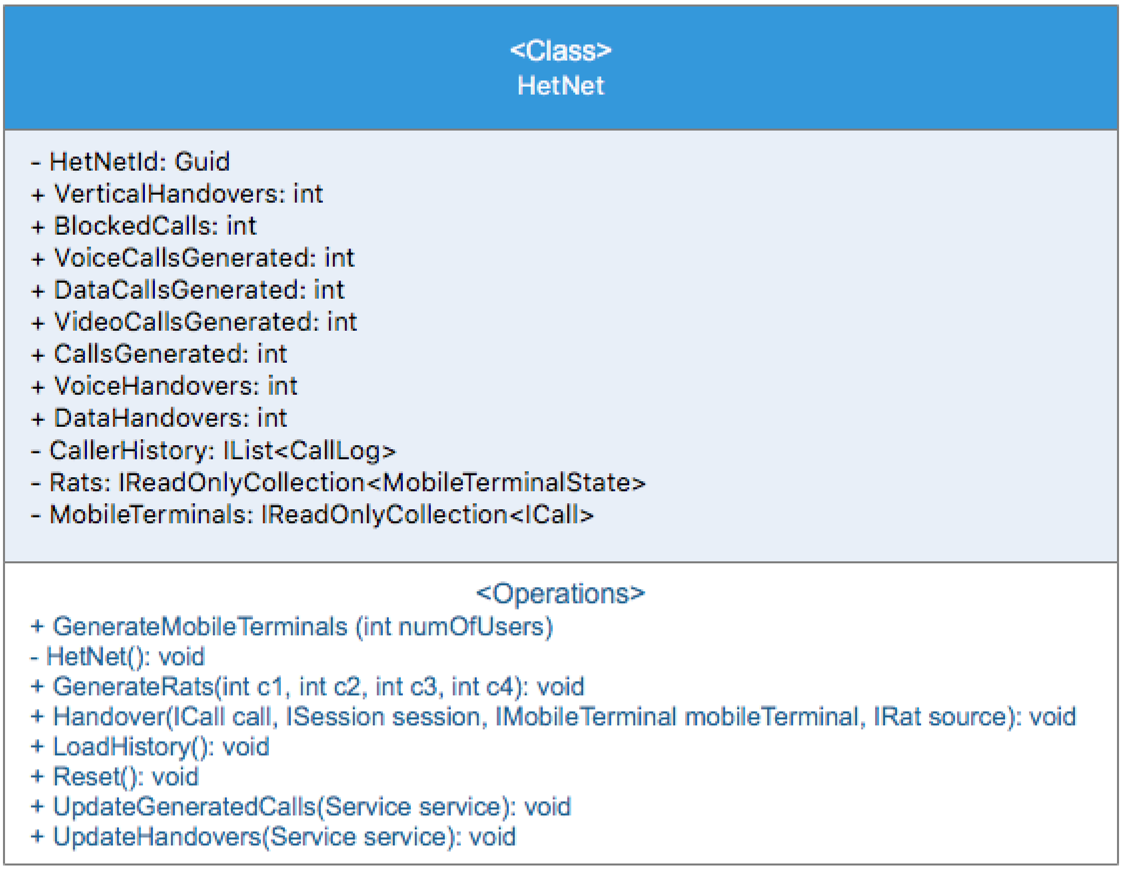


Figure 5.14: UML class diagram of the HetNet class.

Below is a description of the properties and operations found in the HetNet Class

1. ***HetNetId***: Unique identifier of the HetNet

2. ***Rats***: List of all the RATs in the HWN.
3. ***MobileTerminals*:** List to keep track of all the MTs within the HWN
4. ***CallsGenerated***: Keeps track of the number of calls generated in the HWN.
5. ***VoiceCallsGenerated***: Keeps track of the number of voice calls generated in the HWN.
6. ***VideoCallsGenerated***: Keeps track of the number of video calls generated in the HWN.
7. ***DataCallsGenerated***: Keeps track of the number of data calls generated in the HWN.
8. ***TotalSessions***: Keeps track of the total number of sessions that occured in the HWN.
9. ***GenerateMobileTerminals()*:** Generates MTs in the HWN.
10. ***GenerateRats()***: Generates all the RATs in the HWN.
11. ***Handover*(*ICall call, ISession session, IMobileTerminal mobileTerminal, IRAT source*)**: Encapsulates the Handover logic which involves finding the suitable target RAT, transferring ongoing session to a target RAT, releasing network resources in source RAT and allocation of network resources in the target RAT.
12. ***Reset()***: Reset the network parameters when simulation is restarted.

```
namespace VerticalHandoverPrediction.Network
{
    using System;
    using System.Collections.Generic;
    using VerticalHandoverPrediction.CallSession;
    using VerticalHandoverPrediction.Mobile;

    public interface IHetNet
    {
        Guid HetNetId { get; }
        IReadOnlyCollection<IRat> Rats { get; }
        IReadOnlyCollection<IMobileTerminal> MobileTerminals { get; }
        int VerticalHandovers { get; set; }
        int BlockedCalls { get; set; }
        int CallsGenerated { get; set; }
        int VoiceCallsGenerated { get; set; }
        int VoiceHandovers { get; set; }
        int VideoCallsGenerated { get; set; }
        int DataCallsGenerated { get; set; }
        int DataHandovers { get; set; }
        int TotalSessions { get; set; }
        IList<CallLog> CallerHistory { get; set; }

        void GenerateMobileTerminals(int numOfUsers);
        void GenerateRats(int c1, int c2, int c3, int c4);
        void Handover(ICall call, ISession session, IMobileTerminal mobileTerminal, IRat source);
        void LoadHistory();
        void Reset();
        void UpdateGeneratedCalls(Service service);
        void UpdateHandovers(Service service);
    }
}
```

Figure 5.15: C# interface implemented by the HetNet class.

5.3.2 RAT Object

The RAT object models a RAT in the HWN.

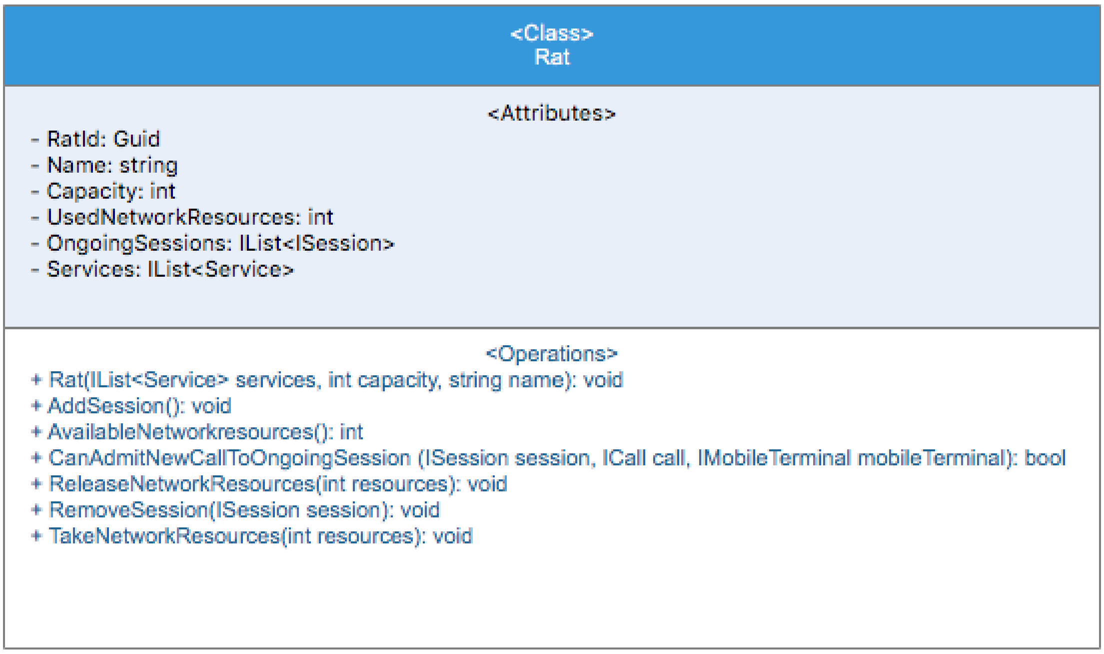
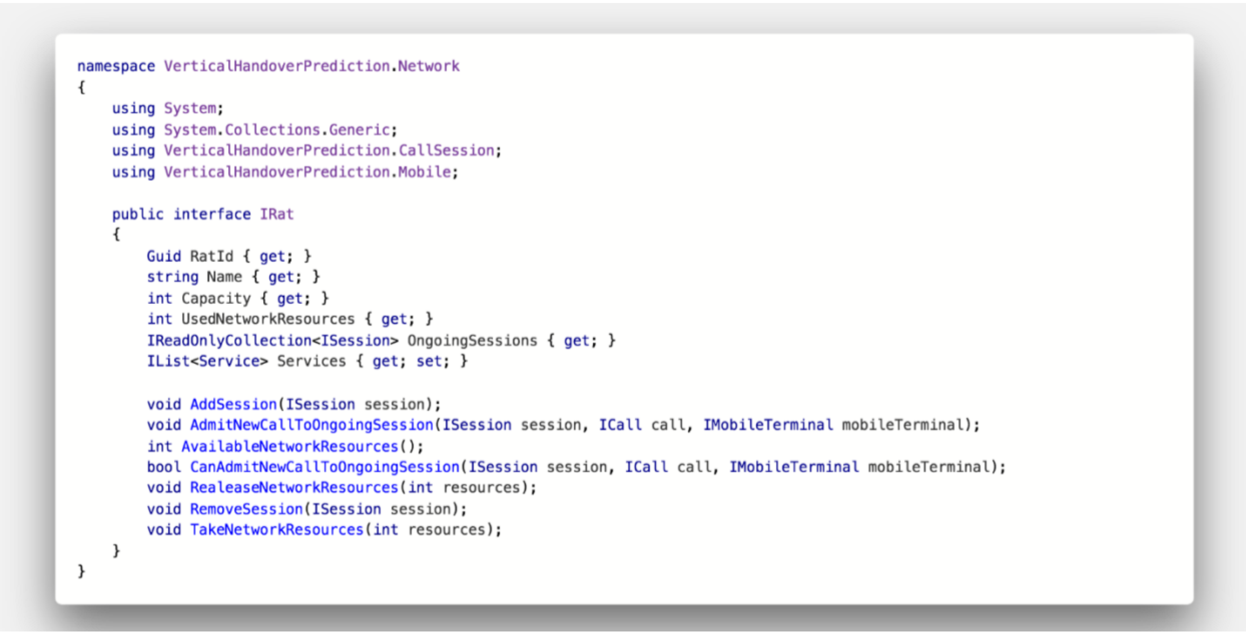


Figure 5.16: UML class diagram of the RAT class.



```
namespace VerticalHandoverPrediction.Network
{
    using System;
    using System.Collections.Generic;
    using VerticalHandoverPrediction.CallSession;
    using VerticalHandoverPrediction.Mobile;

    public interface IRat
    {
        Guid RatId { get; }
        string Name { get; }
        int Capacity { get; }
        int UsedNetworkResources { get; }
        IReadOnlyCollection<ISession> OngoingSessions { get; }
        IList<Service> Services { get; set; }

        void AddSession(ISession session);
        void AdmitNewCallToOngoingSession(ISession session, ICall call, IMobileTerminal mobileTerminal);
        int AvailableNetworkResources();
        bool CanAdmitNewCallToOngoingSession(ISession session, ICall call, IMobileTerminal mobileTerminal);
        void RealeaseNetworkResources(int resources);
        void RemoveSession(ISession session);
        void TakeNetworkResources(int resources);
    }
}
```

Figure 5.17: C# interface implemented by the RAT class.

Below is a description of all the properties and operations of the RAT object.

(1) **RatId**: Unique identifier of a RAT.
(2) **Name:** The name of a RAT.
(3) ***Capacity***: The Capacity of the RAT in basic bandwidth units.
(4) **UsedNetworkResources**: The current number of used basic bandwidth units
(5) **OngoingSessions**: List of all the ongoing sessions on the RAT.
(6) **Services**: List of all the Services supported by the RAT.

(7) **RAT***(IList<Service> services, int capacity, string name):* Constructor used to create a RAT. Upon creation the RatId is generated and the capacity, name and List of services supported by the RAT are initialized.

(8) **AddSession***(ISession session)*: Adds a new session to the RAT.

(9) **AdmitNewCallToOngoingSession***(ISession session, ICall call, IMobileTerminal mobileTerminal):* Admits a new call to an ongoing session on the RAT.

(10) **CanAdmitCallToOngoingSession***(ISession session, ICall call, IMobileTerminal mobileTerminal):* Checks if the session passed in the parameters can be admitted on the RAT(if RAT supports the service and has enough basic bandwidth units to accommodate session)

(11) **ReleaseNetworkResources***(int resources)*: To release the bandwidth unit of RAT when either a on an ongoing session on the RAT is terminated, an ongoing session on the RAT is terminated or when ongoing session on current RAT is transferred to another RAT during a vertical handover.

(12) **RemoveSession***(ISession session)*: Helper method which removes session passed in as a parameter from List of ongoing sessions on the current RAT.

(13) **TakeNetworkResources***(int resources):* Take the network in bandwidth units when a new Call is admitted to a RAT. This also updates the UsedNetworkResources property.

(14) **AvailableNetworkResource**s*():* Returns the number of available network resources on the RAT.

5.4 CallAdmissionControl Module

5.4.1 Cac Object

The Cac object encapsulates all the logic of the proposed call history based one-step forward vertical handover prediction algorithm. It consists of one public method and private helper methods to encapsulate all the logic. See Appendix C for full implementation details of the algorithm.

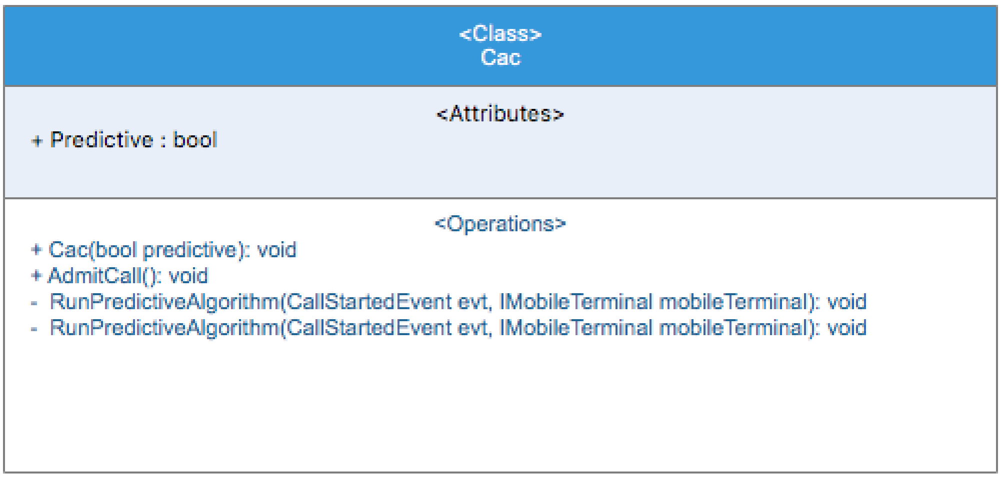


Figure 5.18: UML class diagram of the Cac class.

```
namespace VerticalHandoverPrediction.CallAdimissionControl
{
    using VerticalHandoverPrediction.Simulator.Events;

    public interface ICac
    {
        bool Predictive { get; set; }

        void AdmitCall(CallStartedEvent evt);
    }
}
```

Figure 5.19: C# interface implemented by the Cac class.

The Cac object consist of one public method and 2 private methods

(1) **Cac***(bool predictive)*: Constructor to create a new Cac object for running the predictive algorithm or the non-predictive algorithm. The constructor accepts a Boolean flag to switch between the predictive and non-predictive algorithm during the simulation.
(2) **Predictive**: Property to represent whether the predictive or non-predictive algorithm is being executed.
(3) **AdmitCall***(CallStartedEvent evt)*: Method encapsulates the Call Admission control algorithm. It is the one responsible for invoking the Cac.RunPredictiveAlgorithm method or Cac.RunNonPredictiveAlgorithm method depending on the value of the **Predictive** property flag at the point of execution.
(4) **RunPredictiveAlgorithm***(CallStartedEvent evt, IMobileTerminal mobileTerminal) :* Executes the predictive algorithm.
(5) **RunNonPredictiveAlgorithm***(CallStartedEvent evt, IMobileTerminal mobileTerminal) :* Executes the non-predictive algorithm.

5.5 NetworkSimulator Module

The network simulator module is responsible for orchestrating all the events happening in the HWN and integrating different modules in the system.

5.5.1 Modelling Call Arrivals and Lifetime of a Call

Call Arrivals

Let random variable X denote a arrival of calls in the HWN, where X follows a Poisson process of rate λ. The Equation below shows the probability mass fuction of the process [49]

$$P[X = x] = e^{-x}\frac{\lambda^x}{x!}$$

Equation 5.1: Probability mass function of a poisson process.

Lifetime of call

Let the continuous random variable X denote the lifetime of a call in the HWN, where X has an exponential distribution. [49]

$$X \sim Exponential(\mu)$$

Equation 5.2: Mathematical representation of an event that has an exponential distribution.

And has probability density function

$$f_X(x) = \frac{1}{\mu} e^{\frac{x}{\mu}}$$

Equation 5.3: Probability density function of an exponential distribution.

5.5.2 NetworkSimulator Module and Call Generation

Calls in the HWN are generated as pairs of events namely StartEvent and EndEvent which both implement the IEvent interface as illustrated in Figure 5.15 and Figure 5.16 below.

```
namespace VerticalHandoverPrediction.Simulator.Events
{
    using System;
    using VerticalHandoverPrediction.CallSession;

    public class StartEvent : IEvent
    {
        public Guid EventId { get; set; }
        public Guid CallId { get; set; }
        public Guid MobileTerminalId { get; set; }
        public Service Service { get; set; }
        public DateTime Time { get; set; }
    }
}
```

Figure 5.20: C# implementation of the StartEvent.

```
namespace VerticalHandoverPrediction.Simulator.Events
{
    using System;
    public class EndEvent : IEvent
    {
        public Guid EventId { get; set; }
        public Guid CallId { get; set; }
        public Guid MobileTerminalId { get; set; }
        public DateTime Time { get; set; }

    }
}
```

Figure 5.21: C# implementation of the EndEvent.

Each event has a Time property to store the DateTime at which it should be triggered (where the **EndEvent.Time** must be later than **StartEvent.Time).** Each IEvent object has a CallId property used to keep a reference to the associated call in the HWN.

The pool of events are stored in a Priority Queue data structure which stores the events in order of increasing time event is scheduled to be triggered. The **INetworkSimulator.Run**(*bool predictive*) abstracts all the logic for serving the priority queue and is responsible for triggering the proposed predictive algorithm. Figure 5.22 shows the UML class diagram of the NetworkSimulator class and Figure 5.23 is the C# interface implemented by the NetworkSimulator class.

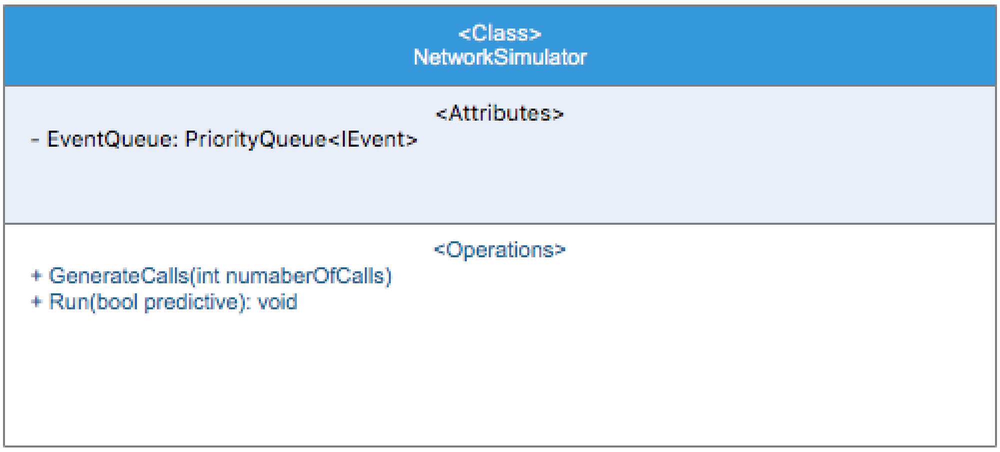


Figure 5.22: UML class diagram of the NetworkSimulator class.

```
namespace VerticalHandoverPrediction.Simulator
{
    using System;
    using System.Collections.Generic;
    using Electron;
    using Medallion.Collections;
    using VerticalHandoverPrediction.Simulator.Events;

    public interface INetworkSimulator
    {
        PriorityQueue<IEvent> EventQueue { get; }
        bool SaveCallLogs { get; set; }
        IList<IEvent> Events { get; set; }

        void GenerateCalls(int numberOfCalls);
        List<Guid> LoadUsers();
        PredictionResults Predict(PredictionParameters data);
        void Run(bool predictive);
    }
}
```

Figure 5.23: C# Interface implemented by the NetworkSimulator class.

See APPENDIX B for the full implementation details of the modules.

Chapter 6 Results and Analysis

In this Chapter, the performance of the predictive VHO algorithm is evaluated by comparison with a non-predictive algorithm. The non-predictive algorithm does not anticipate VHOs in the HWN, thus is only avoids handovers by chance. A comparison of the number of VHOs for both the predictive and non-predictive algorithms is carried out.

6.1 Network Simulation Parameters

Users' call history logs for 20 users are first generated. Table 6.1 and Table 6.2 shows the parameters for the HWN model used for the simulations.

Table 6.1: RAT parameters used for numerical simulations.

	R_1	R_2	R_3	R_4
Services	Voice	Data	Data, Voice	Voice, Data, Video
Capacity (bbu)	$C_1 = 100$	$C_2 = 100$	$C_3 = 100$	$C_4 = 100$

Chapter 5 provides a detailed discussion on the modeling of call arrival and the lifetime of a call in the HWN. The call arrival rate is modeled using a Poisson process with a rate λ and the call duration Is modeled using an exponential distribution with a mean μ. Table 6.2 shows the parameters used for the numerical simulations.

Table 6.2: Parameters used for numerical simulations.

Class of call	Voice	Data	Video
Required bbu	1	2	2
Call Arrival Rate λ	30	40	30
Call Duration μ	(1-15 minutes)	(3 - 20 minutes)	(3-30 mins)

6.2 Analysis of results for the total requested calls

A different number of calls (voice, data, video) were generated in the HWN network and the number of vertical handovers experienced using the predictive VHO algorithm and the non-predictive VHO algorithm is compared. Figure 6.1 shows a comparison of the number of VHOs experienced both algorithms for the same pool of calls. Figure 6.2 shows the number of vertical handovers avoided by the predictive algorithm. The results obtained in Figure 6.1 show that as the number of requested calls increases the number of vertical handovers experienced increases. The results also show that the predictive algorithm reduces the number of vertical handovers experienced in the HWN. The number of vertical handovers is reduced by an average of 70.87% for different pools of calls requested. See APPENDIX C for different simulations using a different pool of calls. The high handover indirectly translates to a high priority given to handover calls. Table 6.3 summarizes the results obtained from the simulation.

Table 6.3: Summary of results for the total requested calls.

Total number of requested calls (voice, data and video)	Number of vertical handovers (non-predictive algorithm)	Number of vertical handovers (predictive algorithm)	% of vertical handovers avoided by predictive algorithm
95	3	1	66.67
172	8	2	75.00
251	19	7	63.16
310	21	5	76.19
385	35	10	71.43
435	45	13	71.11
469	51	14	72.55

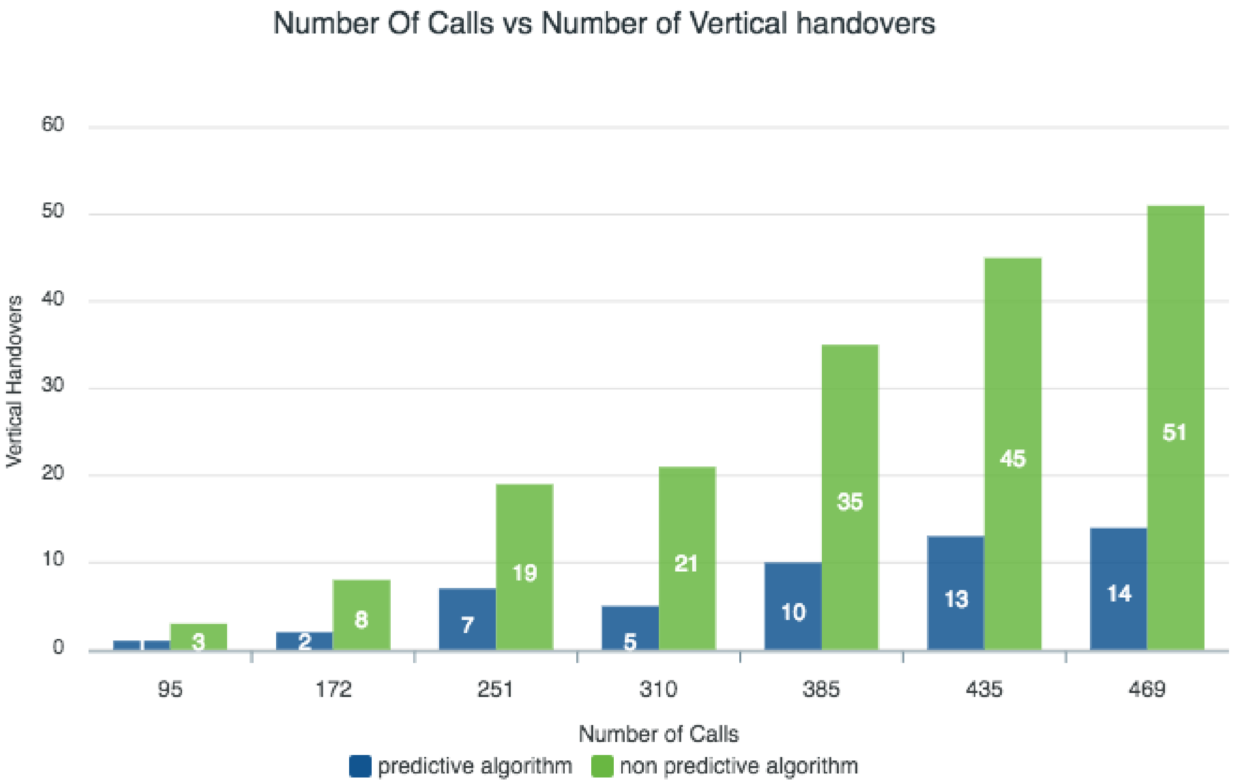


Figure 6.1: Results of number of vertical handovers in HWN for predictive algorithm vs the non-predictive algorithm

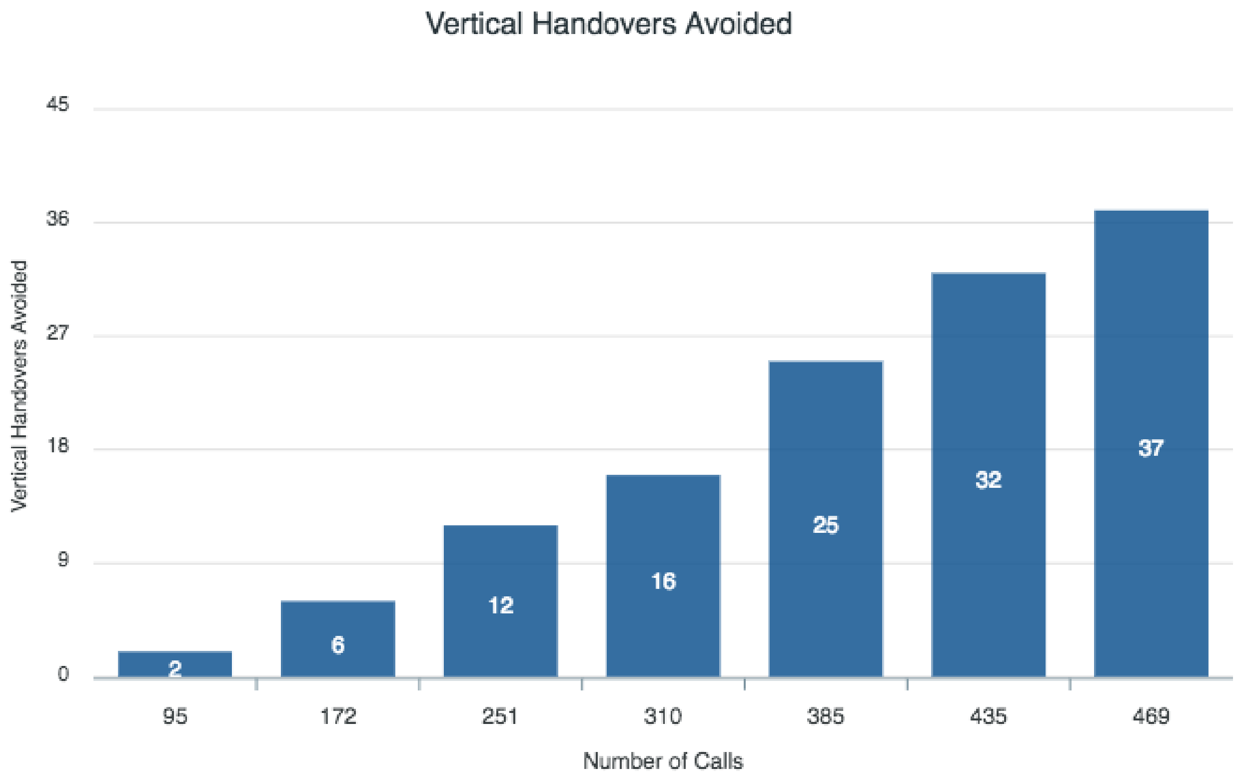


Figure 6.2: Number of vertical handovers avoided by the predictive algorithm for requested voice, data and video calls.

6.3 Analysis of results for the requested voice calls

Figure 6.3 shows a comparison of the number of vertical handovers experienced in the HWN for the predictive VHO algorithm and the non-predictive VHO algorithm for the same pool of total requested voice calls. Figure 6.4 shows the number of VHOs avoided by the proposed algorithm. The results obtained show that the proposed predictive VHO algorithm reduces the number of VHOs experienced in the HWN. The number of vertical handovers for requested voice calls was reduced by an average of 77.4%. Table 6.4 summarizes the results obtained from the simulation.

Table 6.4: Summary of results for requested voice calls.

Number of Requested Voice Calls	**Number of Handovers for non-predictive scheme**	**Number of Handovers for predictive scheme**	**Percentage of Handover Avoided By Handover Scheme (%)**
39	3	1	66.67
60	3	0	100
97	11	3	72.73
121	13	2	84.62
144	19	6	68.42
173	25	7	72
187	35	8	77.14

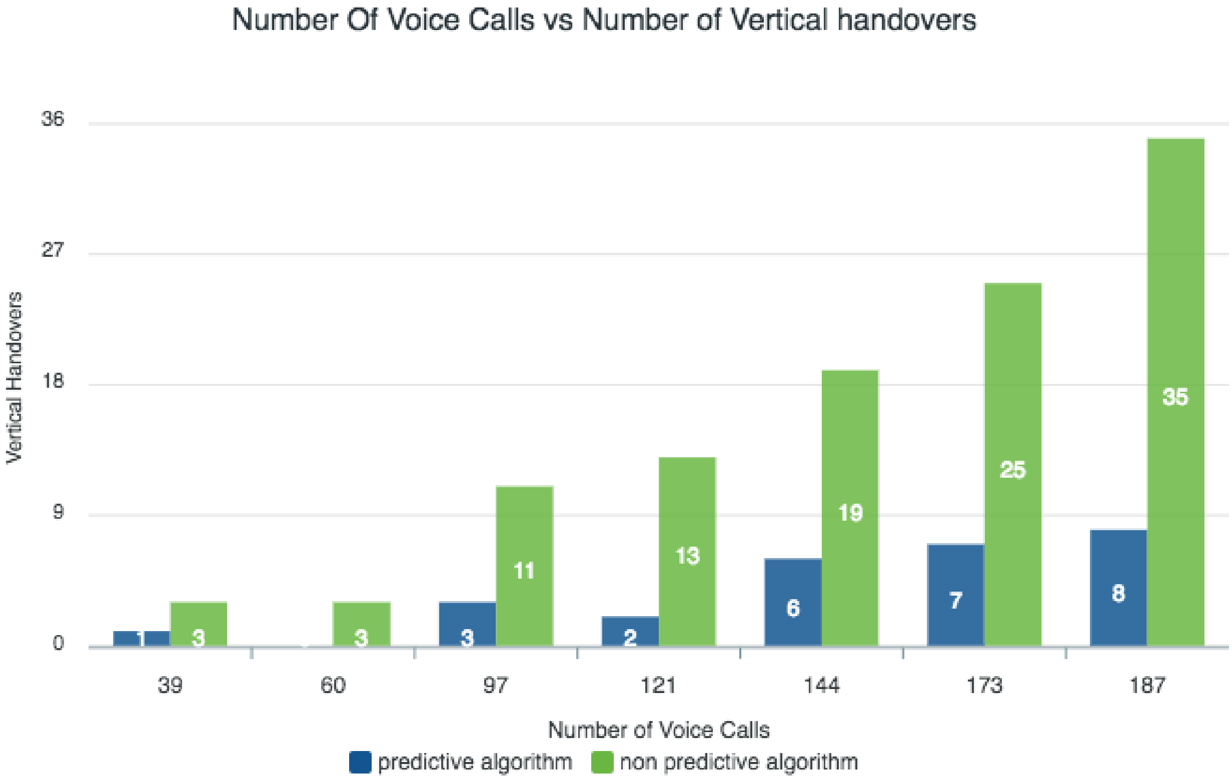


Figure 6.3: Number of vertical handovers in HWN for predictive scheme vs the non-predictive scheme for requested voice calls.

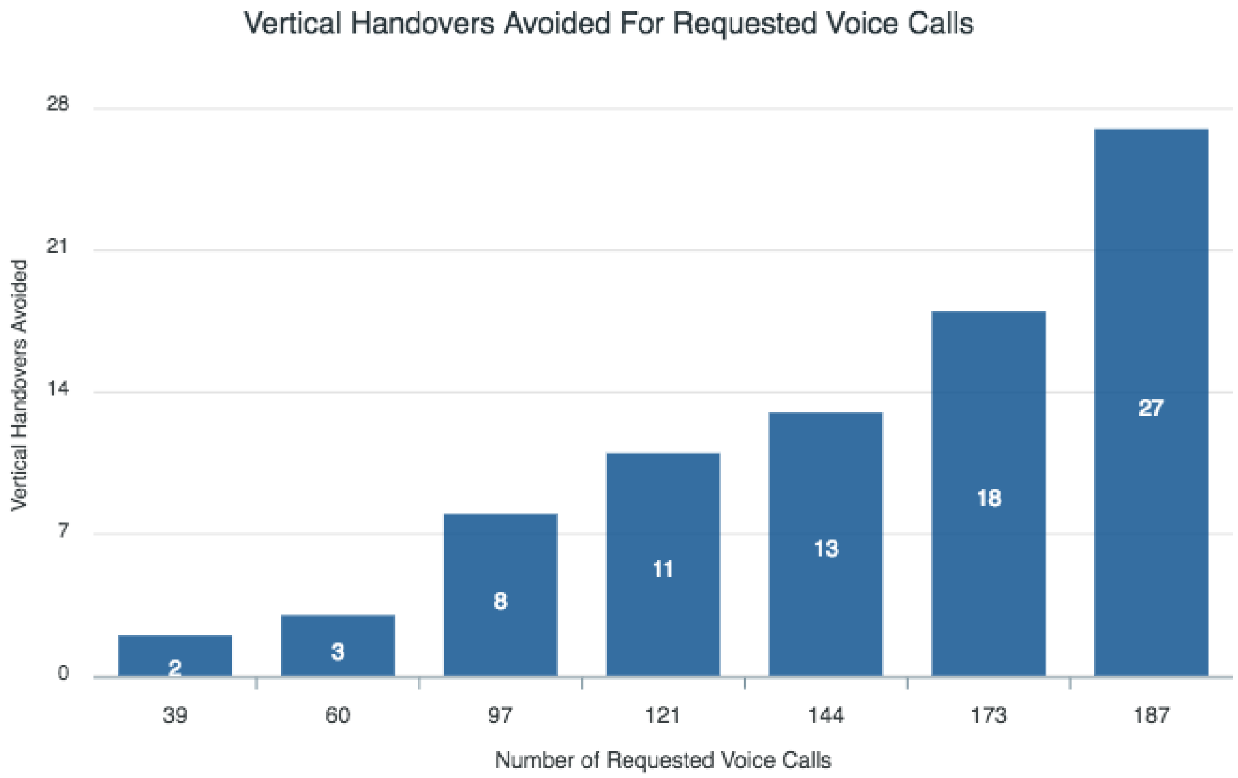


Figure 6.4: Number of vertical handovers avoided by the predictive algorithm for requested voice calls.

6.4 Analysis of results for the requested data calls

Figure 6.5 shows a comparison of the number of vertical handovers experienced in the HWN when using the predictive algorithm and when using the non-predictive algorithm for the same pool of total requested data calls. Figure 6.6 shows the number of vertical handovers avoided by the proposed predictive algorithm. The results obtained show that the predictive VHO algorithm reduces the number of VHOs experienced in the HWN. The number of vertical handovers for requested data calls was reduced by an average of 63.3% which is lower than that for requested voice calls. Table 6.5 summarizes the simulation results.

Table 6.5: Summary of results for requested data calls.

Number of Requested Data Calls	**Number of Handovers for non-predictive scheme**	**Number of Handovers for predictive scheme**	**Percentage of Handovers Avoided By Handover Scheme (%)**
30	0	0	-
56	5	2	60
84	8	4	50
101	8	3	62.5
124	16	4	75
129	20	6	70
143	16	6	62.5

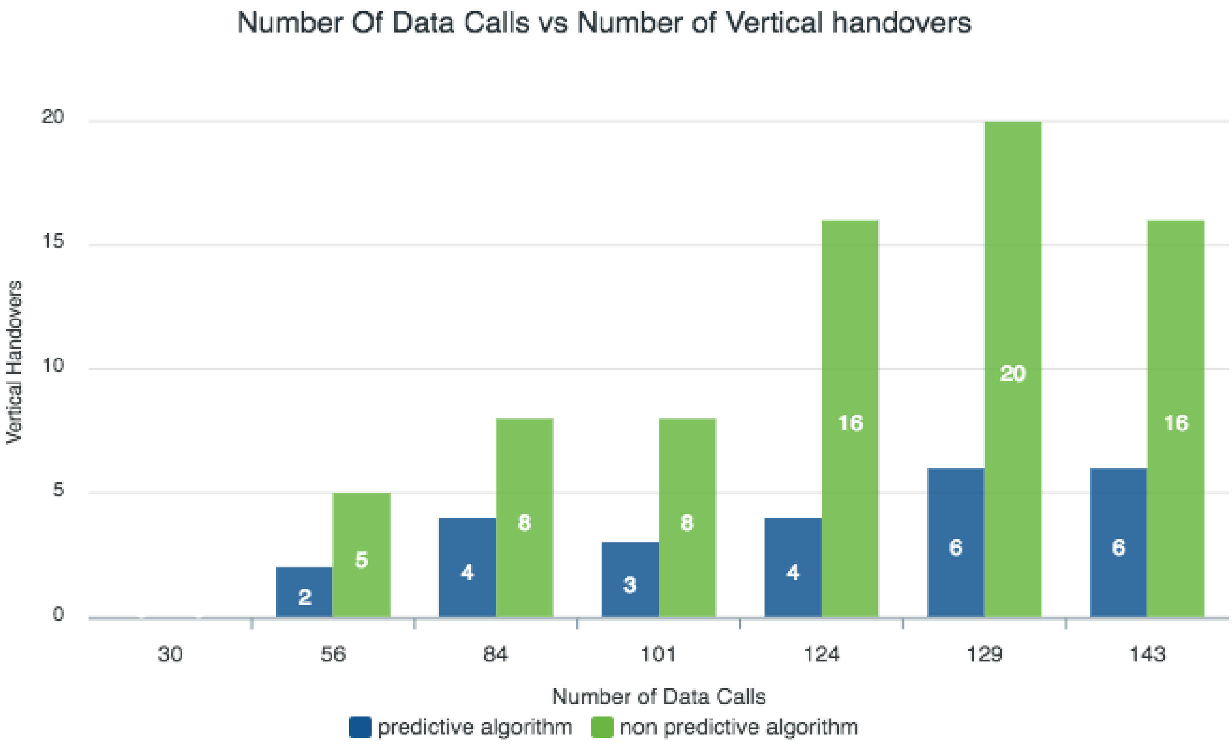


Figure 6.5: Results of the number of vertical handovers in HWN for predictive scheme vs the non-predictive scheme.

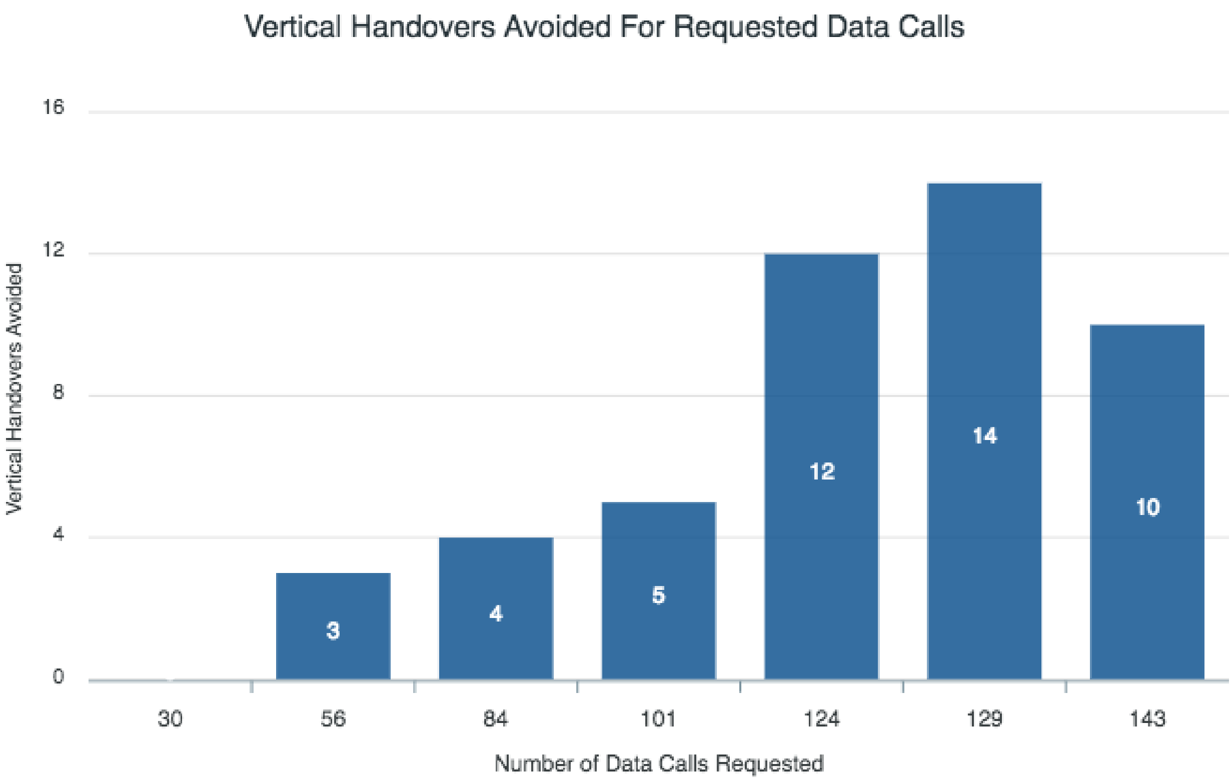


Figure 6.6: Number of vertical handovers avoided by the predictive algorithm for requested data calls.

An analysis of requested video calls cannot be done using the proposed 4 RAT HWN model in this paper. In the HWN model used in this study, only R_4 supports video calls hence the number of vertical handovers experienced for requested video calls will remain zero.

Chapter 7 Conclusion

In this study, an intelligent user's call history-based one-step forward handover prediction and prioritization algorithm was proposed. A simulation environment consisting of 4 RATs and single-homed multi-mode mobile terminals was developed to evaluate the proposed algorithm. The proposed algorithm significantly decreased the number of vertical handovers in the heterogeneous wireless network. The high percentages of vertical handover avoidance translate to a high priority placed on handover calls.

The users' call history logs used in this study were generated randomly hence may not represent real-life user call patterns. It would be interesting to see how the algorithm performs using real-life call history logs.

However, the downside of the proposed algorithm is that in some cases it results in uneven distribution of load among the existing RATs in the heterogeneous wireless networks. Also storing user call history logs may end become heavy for mobile terminals with limited memory capabilities in the long run. Since the algorithm heavily depends on the assumption that subscribers follow regular calling patterns in a network, the algorithm may also fall short on its accuracy for recent changes in user's call patterns

Chapter 8 Recommendations

The following recommendations are made for future and related works

(1) Extend the one-step forward process to N more steps - To improve the prediction accuracy of the algorithm, more N steps can be used in making the handover decision. However, this increases the computational expense of the algorithm.

(2) Test the implemented algorithm on real-life data - The algorithm in this work was not tested using real-life data. It would be interesting to see how the algorithm performs using real-life data which has common patterns followed by users. Analysis of real-life data can enable us to set the prediction confidence [17] in order to improve the accuracy of the proposed algorithm.

(3) Extend the research to investigate the effect of the call dynamics of a multi-homed multi-mode mobile terminal which can aggregate multiple resources from different radio access technologies simultaneously.

(4) Use a sliding window to select only the most recent history in mobile terminals with memory restrictions.

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Appendices

APPENDIX A

Go to link provide and open the README.md for installation instructions

https://github.com/Chitova263/Call-Handover-Prediction-Using-Caller-History

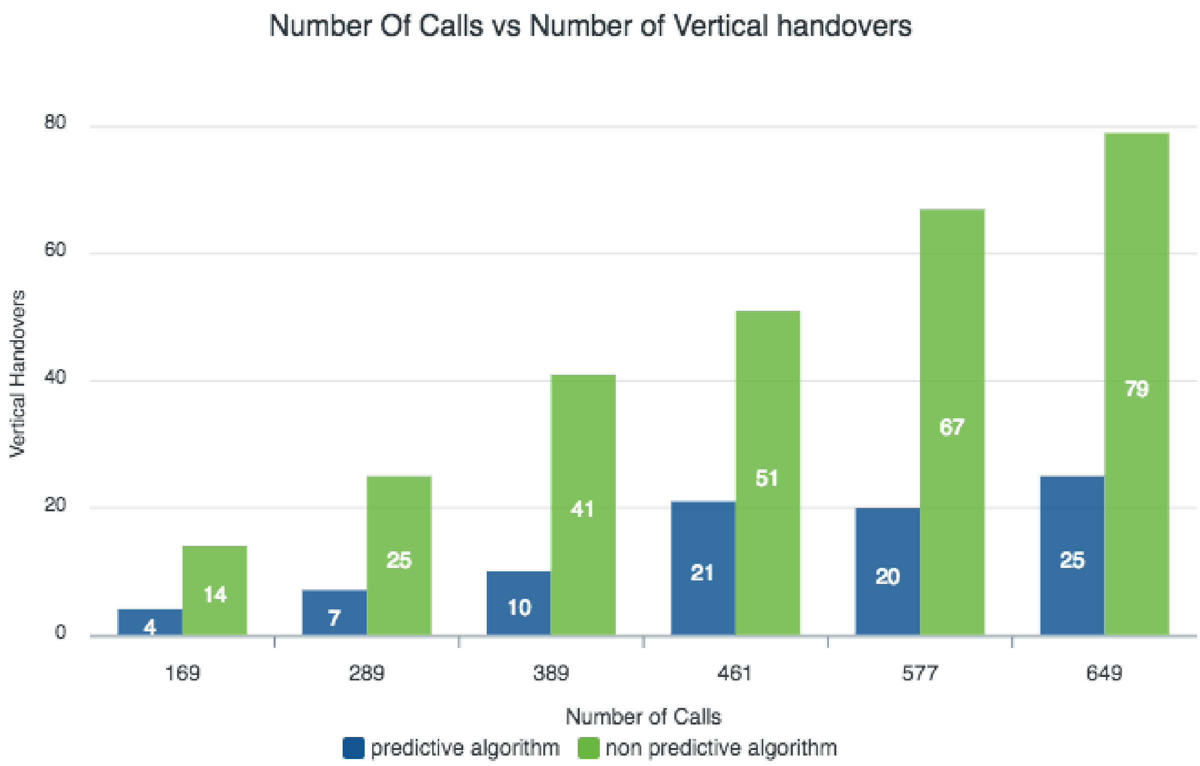
APPENDIX B

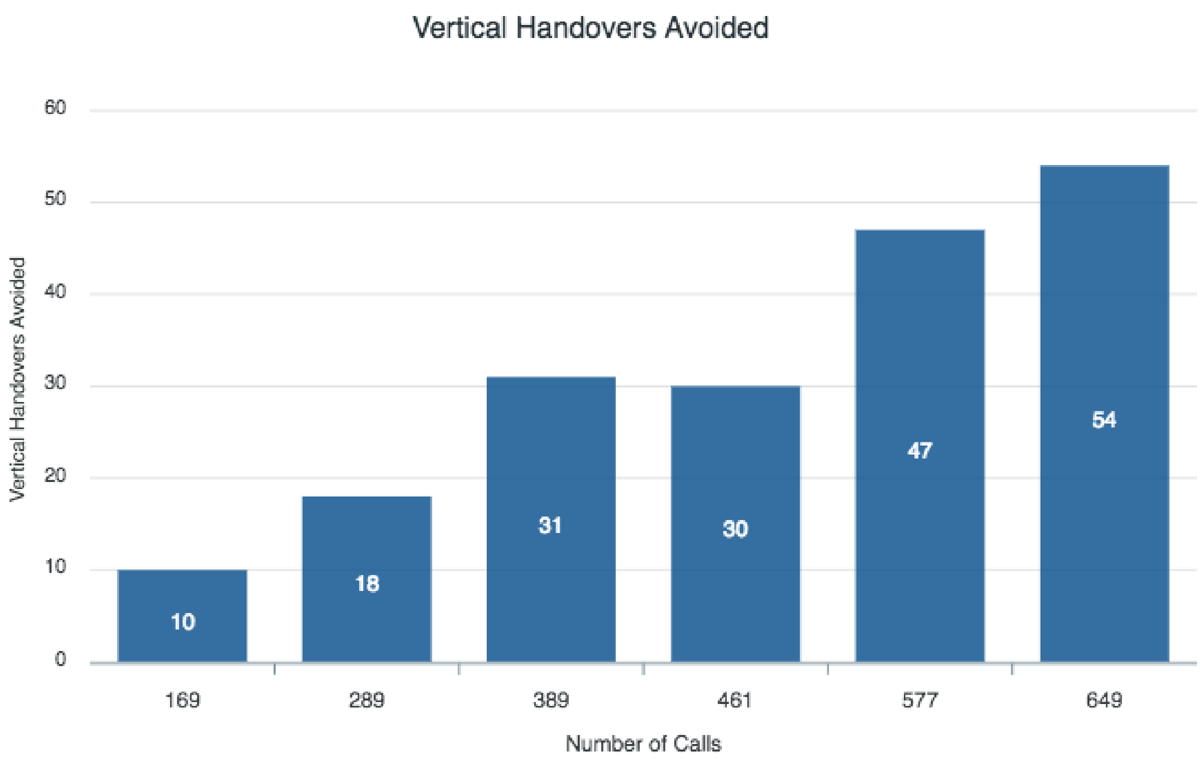
Go to link and navigate to ./src/Core to view C# Code

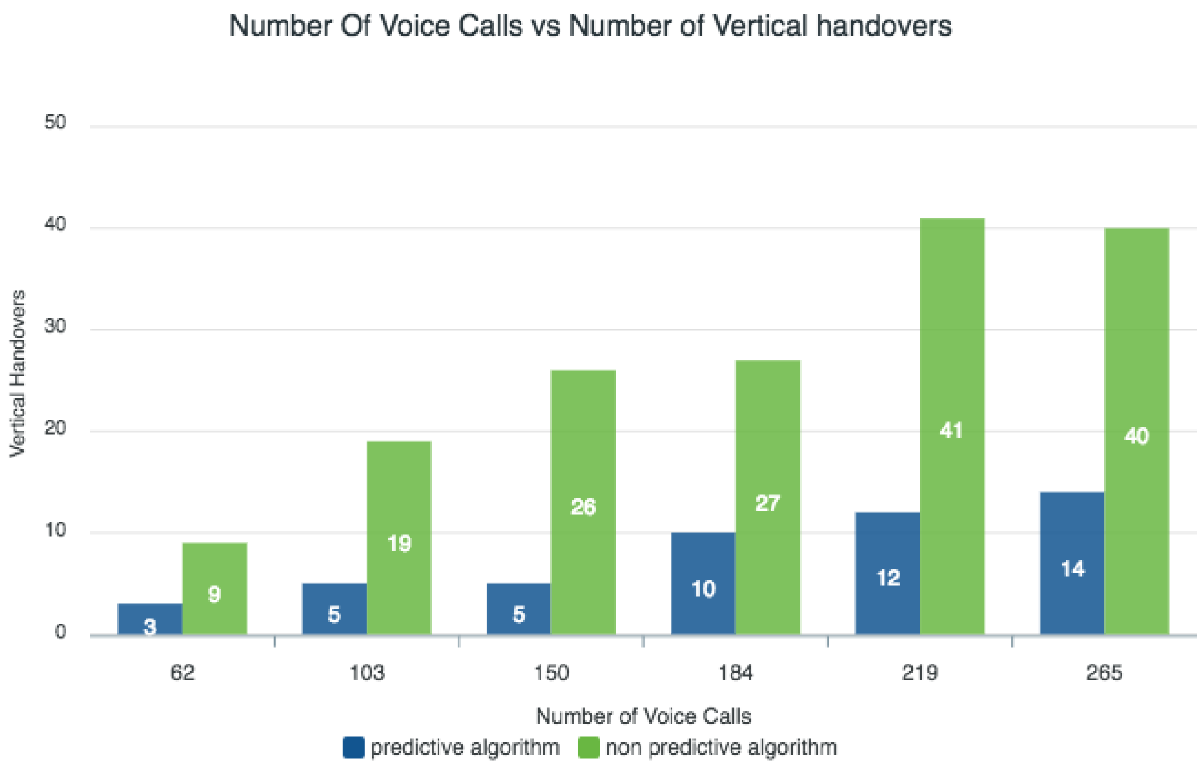
https://github.com/Chitova263/Call-Handover-Prediction-Using-Caller-History

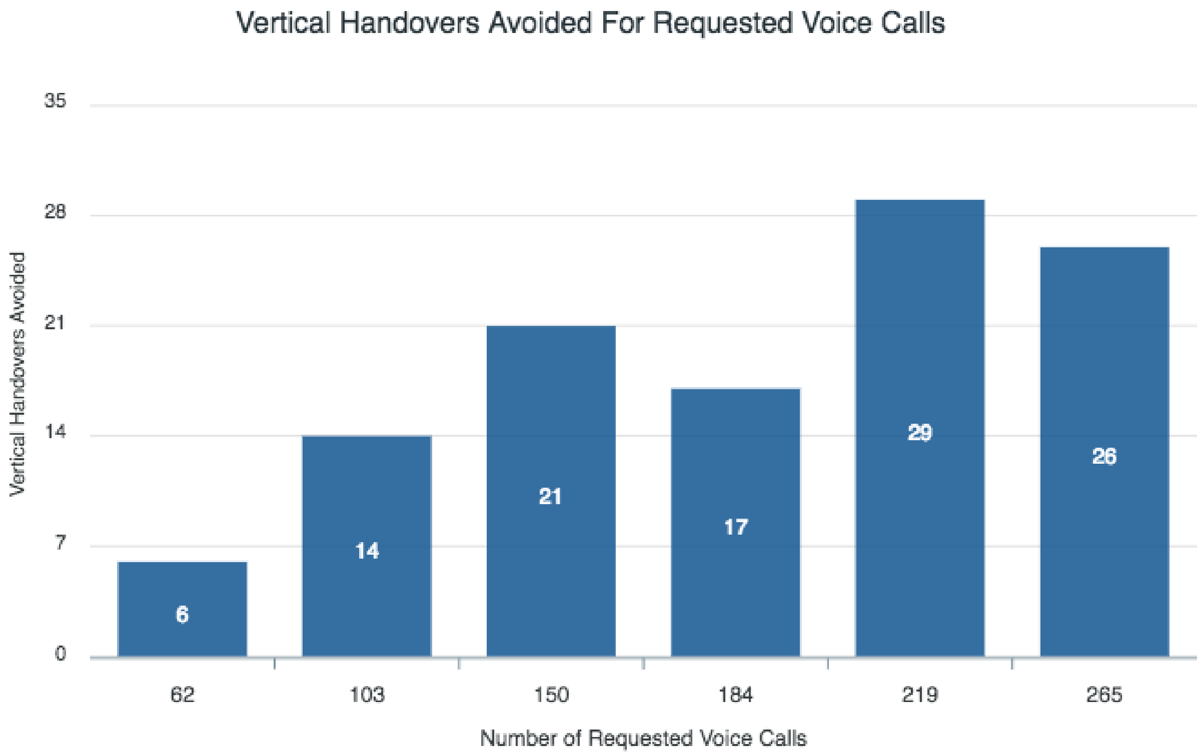
APPENDIX C

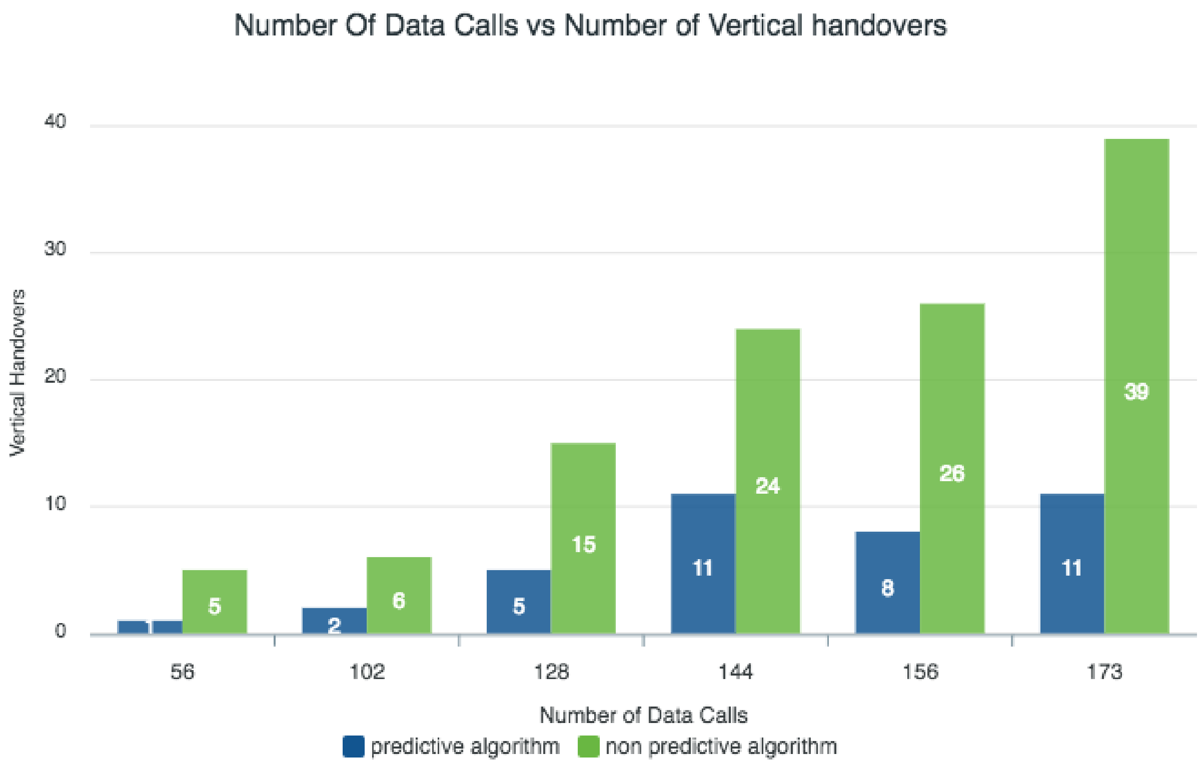
Simulation 1

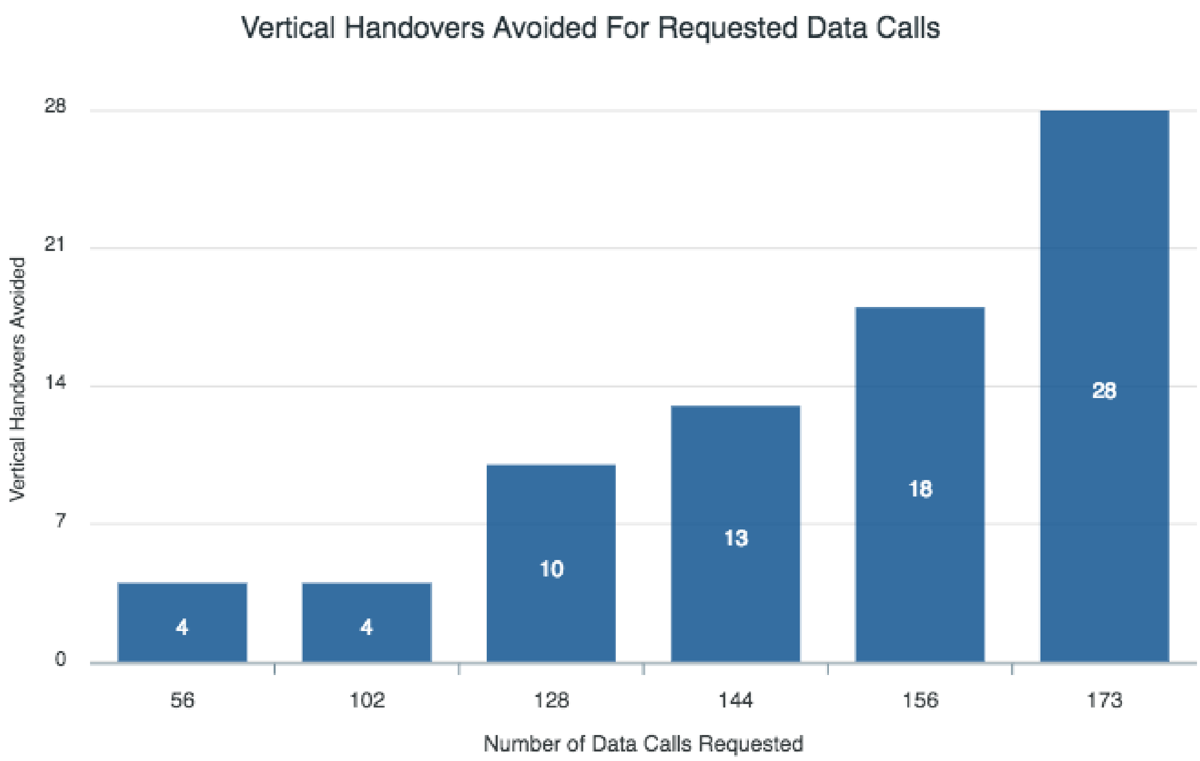



Vertical Handovers Avoided
Vertical Handovers Avoided
60
50
40
30
20
10
0
10
18
31
30
47
54
169
289
389
461
577
649
Number of Calls

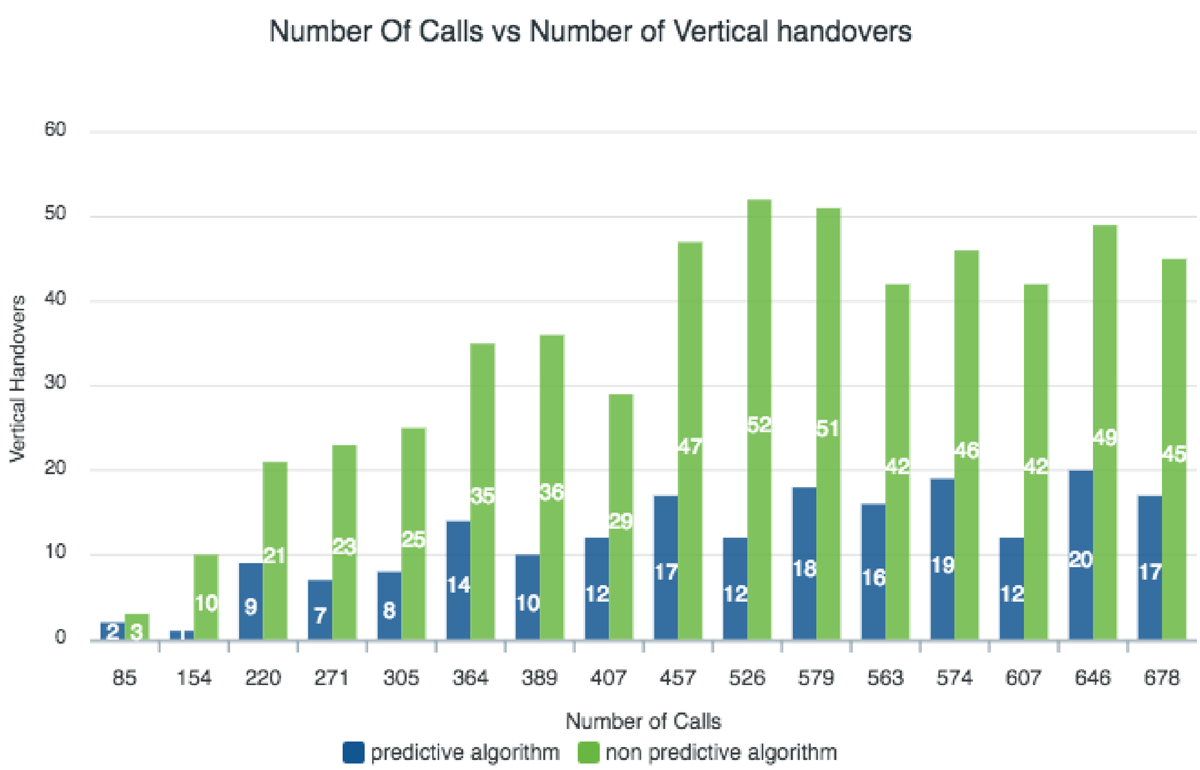

Number Of Voice Calls vs Number of Vertical handovers
Vertical Handovers
50
40
30
20
10
0
3
9
5
19
5
26
10
27
12
41
14
40
62
103
150
184
219
265
Number of Voice Calls
predictive algorithm
non predictive algorithm

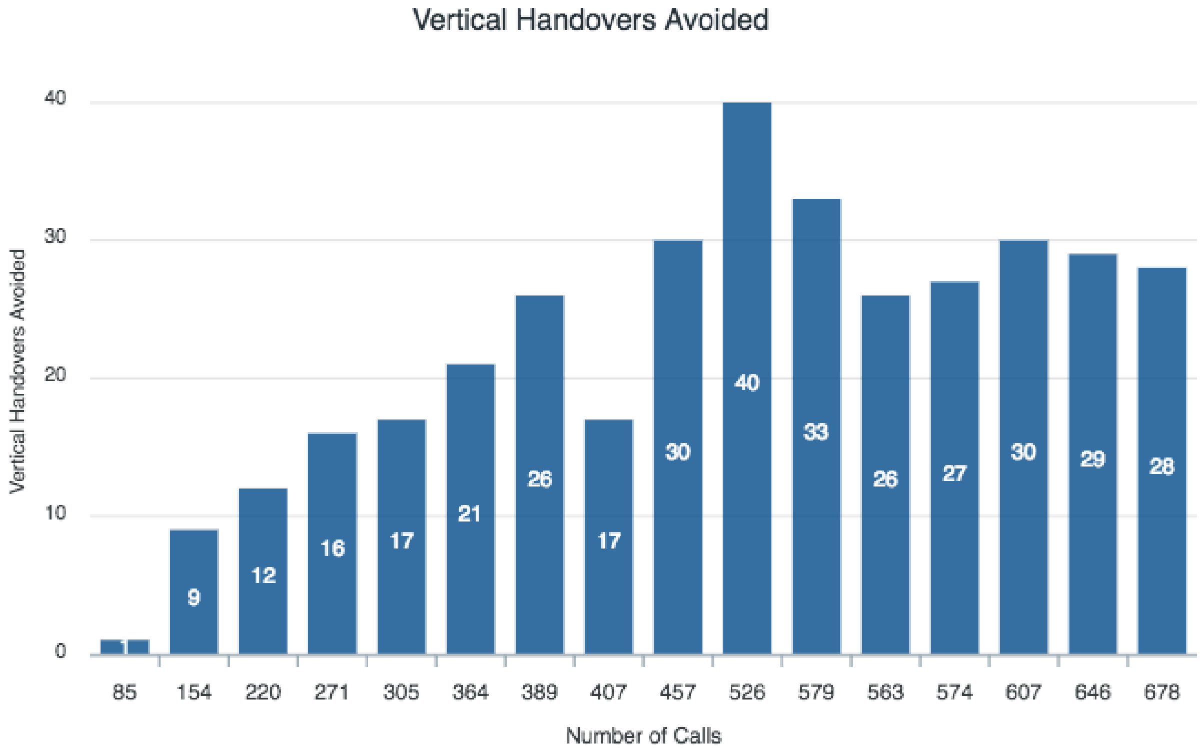

Vertical Handovers Avoided For Requested Voice Calls
Vertical Handovers Avoided
35
28
21
14
7
0
6
14
21
17
29
26
62
103
150
184
219
265
Number of Requested Voice Calls

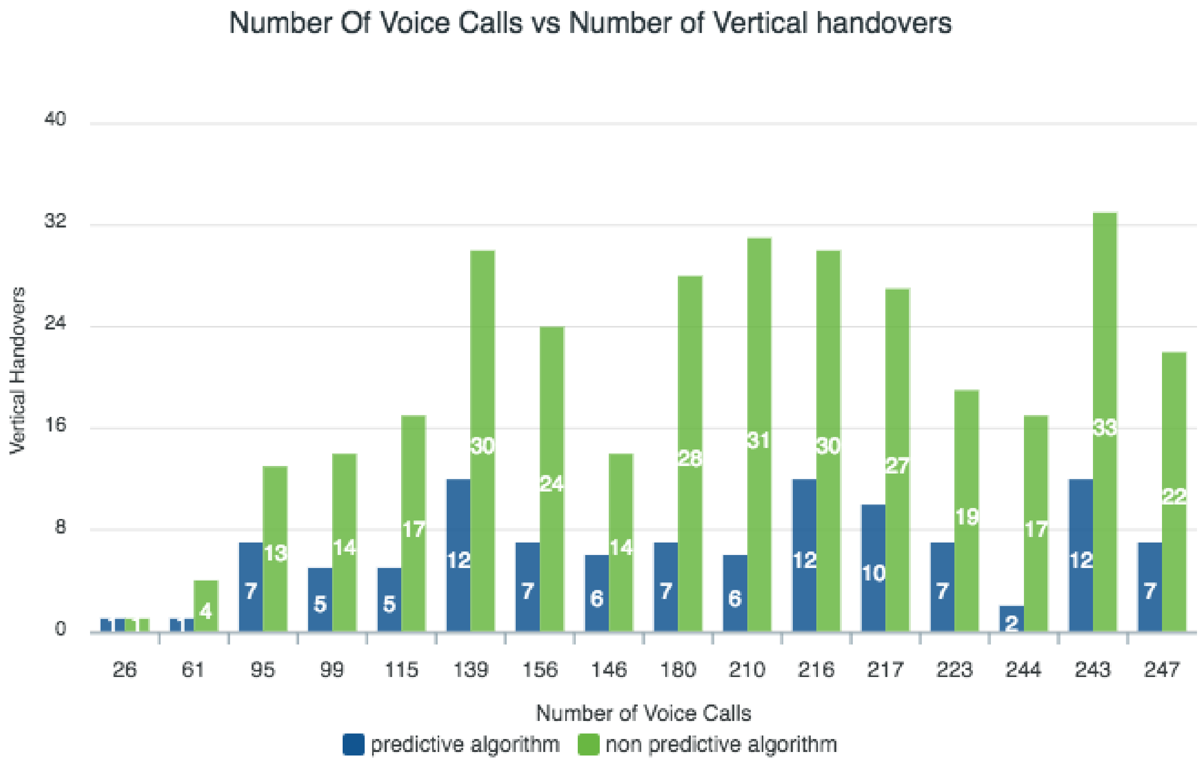

Number Of Data Calls vs Number of Vertical handovers
Vertical Handovers
40
30
20
10
0
5
2
6
5
15
11
24
8
26
11
39
56
102
128
144
156
173
Number of Data Calls
predictive algorithm
non predictive algorithm

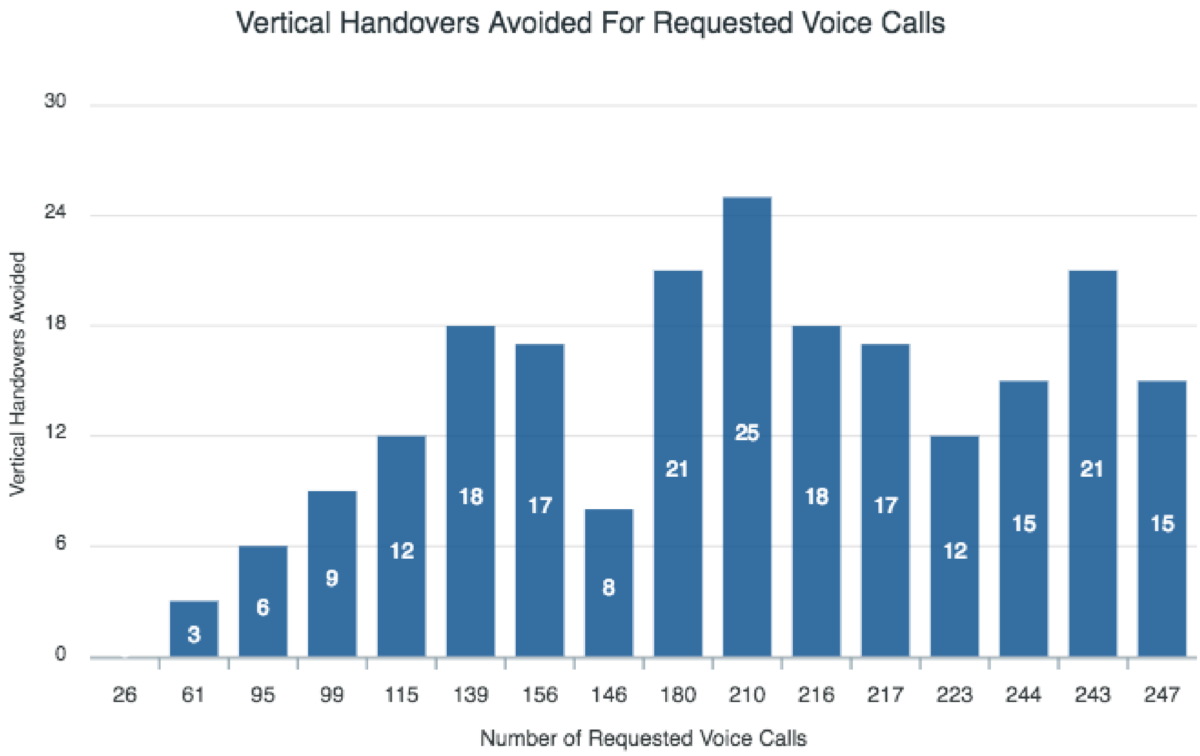


Simulation 2

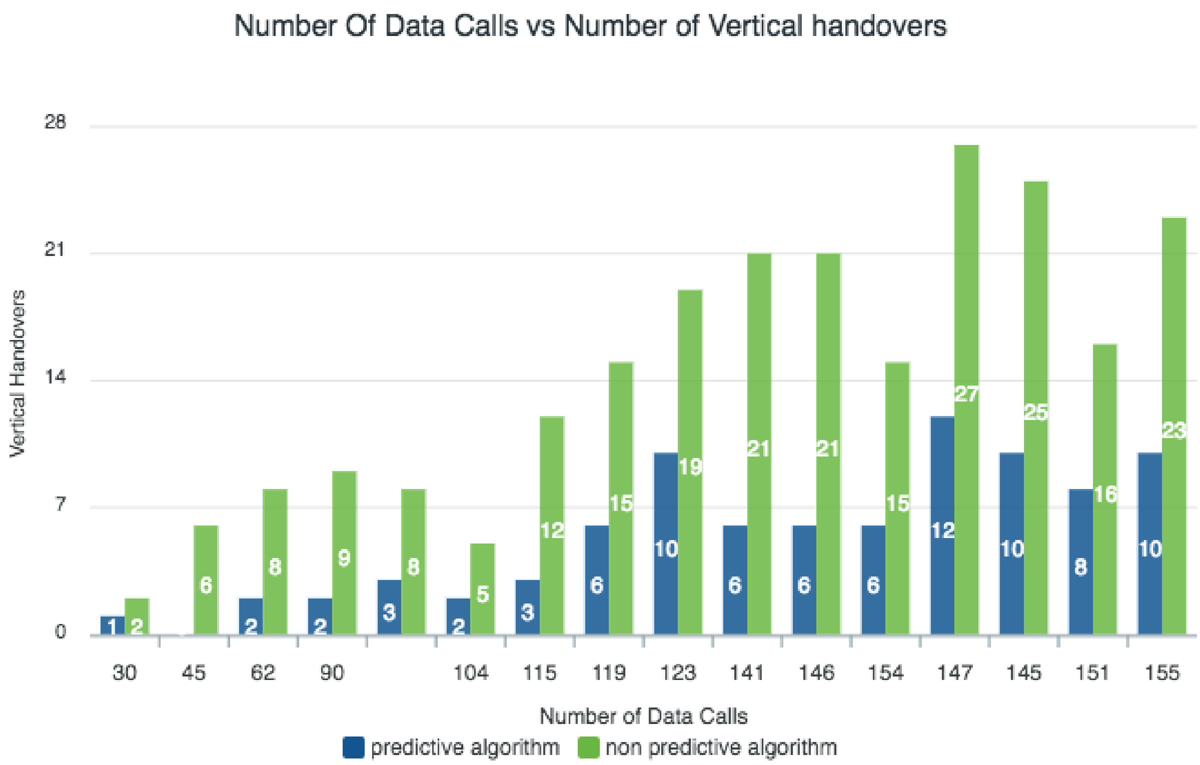



Vertical Handovers Avoided
40
30
20
10
0
Vertical Handovers Avoided
1
9
12
16
17
21
26
17
30
40
33
26
27
30
29
28
85
154
220
271
305
364
389
407
457
526
579
563
574
607
646
678
Number of Calls

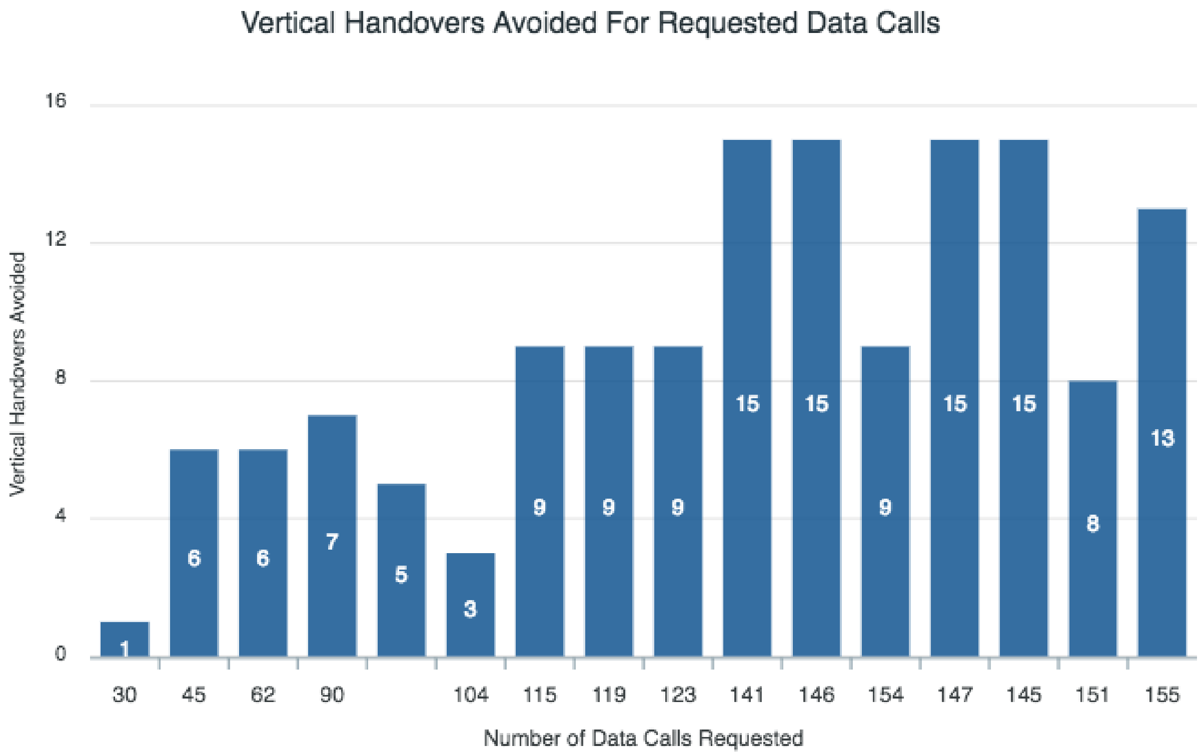

Number Of Voice Calls vs Number of Vertical handovers
40
32
24
16
8
0
Vertical Handovers
7
13
5
14
5
17
12
30
7
24
6
14
7
28
6
31
12
30
10
27
7
19
2
17
12
33
7
22
4
26
61
95
99
115
139
156
146
180
210
216
217
223
244
243
247
Number of Voice Calls
predictive algorithm
non predictive algorithm



Vertical Handovers Avoided For Requested Voice Calls
Vertical Handovers Avoided
Number of Requested Voice Calls
30
24
18
12
6
0
26 61 95 99 115 139 156 146 180 210 216 217 223 244 243 247
3 6 9 12 18 17 8 21 25 18 17 12 15 21 15



Number Of Data Calls vs Number of Vertical handovers
Vertical Handovers
Number of Data Calls
28
21
14
7
0
30 45 62 90 104 115 119 123 141 146 154 147 145 151 155
1 2 6 2 8 2 9 3 8 2 5 3 12 6 15 10 19 6 21 6 21 6 15 12 27 10 25 8 16 10 23
predictive algorithm
non predictive algorithm


Vertical Handovers Avoided For Requested Data Calls
Vertical Handovers Avoided
Number of Data Calls Requested
0
4
8
12
16
30
45
62
90
104
115
119
123
141
146
154
147
145
151
155
1
6
6
7
5
3
9
9
9
15
15
9
15
15
8
13