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I, Wei Shen,
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This work and its defense approved by:

Chair: Qing-An Zeng
Kenneth Berman
Raj K. Bhatnagar
Wen-Ben Jone
Heng Wei

NETWORK SELECTION STRATEGIES AND RESOURCE MANAGEMENT
SCHEMES IN INTEGRATED HETEROGENEOUS WIRELESS AND MOBILE
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by
Wei Shen

B.Eng, Anhui Normal University, 1997

M.Eng., Nanjing University of Posts & Telecommunications, 2001

Thesis Advisor and Committee Chair: Dr. Qing-An Zeng

ABSTRACT

Wireless and mobile networks (WMNs) are witnessing a great success in recent years. Although there are different types of WMNs (e.g., cellular networks, WLANs, etc.) that can provide different types of services (e.g., different bandwidth and coverage), any single type of existing WMN is not able to provide all types of services such as high bandwidth with wide coverage. In order to provide more comprehensive services, a concept of integrated heterogeneous wireless and mobile network (IHWMN) is introduced by combining different types of WMNs. Additionally, with the advance of software defined radio (SDR) technologies, it is possible to integrate multiple WMN interfaces into a single mobile terminal and let the terminal be able to access multiple WMNs. It is obvious that the introduction of IHWMN as well as multi-interface terminal brings more flexible and plentiful access options for mobile users. However, it faces great challenges, such as the architecture of network integration, network selection strategies, handoff scheme, resource allocation, etc. Although IHWMN is a very promising candidate for the future WMNs, a lot of problems have to be solved before launching to the commercial market.

In this research thesis, we briefly review the existing work for IHWMN. Then, traffic and system models are proposed for IHWMN. Based on the proposed models, we tackle the network selection problem in IHWMN, which is required to determine which network should be accessed. A cost-function-based network selection (CFNS) strategy is proposed based on sys-

tem's perspective, which also takes into account of the user's needs. Theoretical model is used to evaluate the system performance of the proposed CFNS strategy and simulations are also conducted to verify our analysis. Then, we propose preemption-based resource management schemes to support real-time and non-real-time traffic in IHWMNs. The proposed resource management schemes take advantage of heterogeneities of multiple traffic and networks as well as moving nature of users. We further design an algorithm to achieve the fairness between the real-time and non-real-time traffic. The analytical results show that the proposed resource management schemes provide the best service to non-real-time traffic while satisfying the QoS requirements of real-time traffic. In the last, we address the resource management from different perspective. A traffic-based resource management scheme (TRMS) is firstly introduced, which takes advantage of the heterogeneity of traffic and networks as well as user's satisfaction. We then use Markov decision process to model the resource management scheme of multiple traffic in IHWMNs and propose a Q-learning-based resource management scheme (QRMS) to allocate the resource. The issues addressed in this thesis provide many insights into characterizing the emerging problems in IHWMNs. The analytical and simulation methods applied in this thesis will be useful for the research and development in IHWMNs.

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List of Abbreviations

1G	the first generation
2G	the second generation
3G	the third generation
3GPP	the third Generation Partnership Project
AMPS	Advanced Mobile Phone System
AP	access point
BBU	basic bandwidth unit
BS	base station
CFNS	cost-function-based network selection
D-AMPS	Digital AMPS
DVH	downward vertical handoff
EDGE	Enhanced Data Rates for GSM Evolution
GPRS	General Packet Radio Service

GSM	Global System for Mobile Communications
IHWMN	integrated heterogeneous wireless and mobile network
IMT-2000	International Mobile Telecommunication-2000
IP	Internet Protocol
ITU	International Telecommunication Union
PCS	Personal Communication Services
PDC	Personal Digital Cellular
pdf	probability density function
QoS	Quality of Service
QRMS	Q-learning-based resource management scheme
RSNS	received signal strength-based network selection
SDR	software defined radio
SOR	successive overrelaxation
TBNS	traffic balance-based network selection
TRMS	traffic-based resource management scheme
UMTS	Universal Mobile Telecommunication System
UVH	upward vertical handoff
WCDMA	Wide-band Code Division Multiple Access
WiMax	Worldwide Interoperability for Microwave Access

WLAN Wireless Local Area Network

WMN wireless and mobile network

Chapter 1

Introduction

1.1 History of Wireless and Mobile Networks

Wireless and mobile networks (WMNs) attract a lot of attention in both academical and industrial fields. Generally, WMN can be classified into two types, centralized (or infrastructure-based) and distributed (or infrastructure-less) WMNs. In the following, the history of both types of WMNs are briefly reviewed.

Cellular networks are the most widely deployed centralized WMNs. The earliest cellular networks are analog systems, which are referred to as the first generation (1G) cellular networks. The 1G cellular networks started their services since 1979 [1]. Advanced Mobile Phone System (AMPS) was the primary 1G cellular network that was widely deployed in North America [1]. However, the spectrum efficiency and system capacity of the analog cellular networks cannot meet the rapidly increasing needs of mobile users. Therefore, digital cellular networks were introduced to improve the spectrum efficiency, security, service quality, and system capacity, which are called the second generation (2G) cellular networks. Many 2G cellular networks were

deployed in 1990s [2], including Global System for Mobile Communications (GSM), Personal Digital Cellular (PDC), Digital AMPS (D-AMPS), Personal Communication Services (PCS), IS-95 systems, etc., [1]. In order to provide higher data transmission rate and more flexible communication capability, the third generation (3G) cellular networks, IMT-2000 (International Mobile Telecommunication-2000), were introduced by International Telecommunication Union (ITU) in 1999 [3]. Due to the big jump of technologies from 2G to 3G cellular networks, many enhanced 2G networks are designed as the interim cellular networks from 2G to 3G [2]. These interim cellular networks, called 2.5G, include IS-95B [4], Enhanced Data Rates for GSM Evolution (EDGE) [5], and General Packet Radio Service (GPRS) [6]. For the 3G cellular networks, Wide-band Code Division Multiple Access (WCDMA) has been commercialized at Japan in 2001, and Universal Mobile Telecommunication System (UMTS) are now operating in Europe and Australia. The cdma2000 standard is the choice for the 3G cellular networks in North America [1]. The IEEE 802.11 WLANs (Wireless Local Area Networks) [1] are other types of centralized WMNs. Because WLANs are easy to deploy and can provide high bandwidth service, they have experienced rapid growth and wide deployment since their birth.

Generally, the service area of a cellular network is divided into multiple small areas that are called cells. Each cell has a central control unit that is referred to as base station (BS). All the communications in the cellular network take place via the BSs. That is, the communication between a mobile user in a cellular network and others (either inside the same cellular network or outside the cellular network) must be relayed through a BS. In a WLAN, the central control unit is called access point (AP). Similar to cellular networks, the communications in a WLAN must be via the APs. The BSs or APs are connected to the backbone networks and provide connections with other external networks, such as Public Switched Telephone Network (PSTN) and Internet. HIPERLAN [7], satellite networks, and Worldwide Interoperability for Microwave

Access (WiMAX) [8] also belong to the centralized WMNs.

Unlike centralized WMNs, there is no fixed network structure in a decentralized (or distributed) WMN. Wireless and mobile ad hoc networks is a typical distributed WMN that attracts a lot of research interests recently [1]. The wireless and mobile ad hoc network is dynamically created and maintained by the nodes. The nodes forward packets to/from each other via a common wireless channel without the help of any wired infrastructure. When a node needs to communicate with other nodes, it needs a routing discovery procedure to find a potential routing path to the destination node. Due to frequent movement of communication nodes, the routing path between two communication nodes is not fixed. When a relay node moves out of transmission range of other communication nodes, the current routing path is broken. As a result, another routing path has to be found in order to keep the communication alive. Wireless and mobile ad hoc networks are very useful in some areas that a centralized WMN is not possible or inefficient, such as disaster recovery and battle field [1].

1.2 Integrated Heterogeneous Wireless and Mobile Networks

Although there are many different types of WMNs that can provide different types of services such as different coverage and bandwidth, any single type of existing WMN is not able to provide all types of services, such as high bandwidth with wide coverage. For example, the 2G cellular networks, like GSM or IS-95 system, provide voice service with a good quality in a wide area but limited bandwidth. The IEEE 802.11 WLANs can provide high bandwidth service only in hotspots. In order to provide more comprehensive services such as high bandwidth with wide coverage, an *integrated heterogeneous wireless and mobile network* (IHWMN) is introduced by combining different types of networks. That is, an IHWMN is an integration of heterogeneous

wireless and mobile networks. Figure 1.1 shows a example of an IHWMN, which consists of satellite networks, cellular networks, WLANs and ad hoc networks.

Figure 1.1: An integrated heterogeneous wireless and mobile network

Additionally, due to the advances of integrated circuits design and SDR (software defined radio) technologies, it is possible to have multiple network interfaces in a single mobile terminal. Such multi-interface terminal is also called *multi-mode terminal* because it can support multiple communication modes. That is, a mobile user having a multi-mode terminal can access different types of networks in an IHWMN, which provides more flexible and plentiful access options. Currently, there are multi-mode cards available in the market, such as Nokia D211 [9] and Option Fusion 3G/GPRS/GSM/WLAN PC Card [10]. These cards can provide multiple network communication capabilities.

1.3 Preliminary

Although an IHWMN can provide more comprehensive services than any single type of existing WMN, it imposes great challenges, such as interworking among different types of WMNs, network selection strategies, and resource management schemes. In the following, basic knowledge and terms about IHWMNs are briefly reviewed.

- Interworking (or Interconnecting) is a basic requirement to integrate different types of WMNs, which specifies how different types of WMNs cooperate with each other.
- When a mobile user having a multi-mode terminal generates a new (or originating) call in an IHWMN, it needs a network selection strategy to determine which network should be accessed.
- In a traditional single type of cellular or WLAN network, an active mobile user (in communication) may move from one cell to another cell. In order to keep the communication alive, the connection has to be changed from one BS (or AP) to another BS (or AP). Such process of changing the connection within the same network is called *handoff* [11]. In this thesis, we define such handoff as *horizontal handoff*. For example, the handoff between two adjacent cellular network cells in Figure 1.1 is a horizontal handoff. In an IHWMN, the connection may be changed from one network to another network for better service. Such process of changing the connection between two different types of networks is called *vertical handoff*. For example, the handoff between cellular network and WLAN in Figure 1.1 is a vertical handoff. Since the vertical handoff happens between two different types of networks, it is also known as *inter-network handoff*. The horizontal handoff can be called *intra-network handoff*. Compared to horizontal handoff, vertical handoff is more complex

and brings a lot of issues such as vertical handoff decision and vertical handoff execution, need to be handled carefully. The horizontal handoff has to be made in order to keep the communication in the traditional cellular networks or WLANs. Obviously, horizontal handoff is mandatory. Vertical handoff is more complicated than horizontal handoff, which can be divided into two categories. If an active mobile user roams into a new network which provides better service than the current serving network, it may request a vertical handoff and change the connection to the better network. Unlike the horizontal handoff that is mandatory, this type of vertical handoff is optional and is called *downward vertical handoff* (DVH) [12]. Because the mobile user may still keep its communication with the current serving network. On the other hand, when an active mobile user moves out the coverage of its current serving network, it has to make a vertical handoff to other available networks. Such type of vertical handoff is called *upward vertical handoff* (UVH) [12]. Similar to the horizontal handoff, the UVH is mandatory since a failed vertical handoff terminates the communication.

- With the rapid emergence of multimedia contents (e.g., voice, data, and video), different types of traffic have to be supported in WMNs. Generally, multiple traffic can be classified into real-time traffic (e.g., voice and video) and non-real-time traffic (e.g., data) based on their sensitivities to the delay. The major challenge to support multiple traffic is that different types of traffic are incorporated into one system and each traffic has its distinct requirements of Quality of Service (QoS). For example, real-time traffic is delay-sensitive, while non-real-time traffic is delay-tolerant. Based on traffic's features, a resource management scheme has to treat them differently and satisfy their individual requirements of QoS. In IHWMNs, the resource management becomes more challenging due to the diversity of the services provided by heterogeneous WMNs. Another challenging issue has

to be handled in multiple traffic system is the fairness among different types of traffic. That is, some low priority traffic obtains poor performance while some high priority traffic obtains over-qualified services.

1.4 Motivations and Contributions

The integration of heterogeneous WMNs is not an easy task, which has a lot of open issues such as network selection strategies and resource management schemes.

In our knowledge, there are some network selection strategies have been proposed for IH-WMNs [13] [14] [15] [16] [17]. Although these network selection strategies have their own advantages, most of them are designed to meet individual mobile user's needs, such as only considering bandwidth or power consumption. In other words, they are user-centric. They do not put much attention on system performances, such as the blocking probability of originating calls and the forced termination probability of ongoing calls (or handoff calls). The motivation of this research work is to design a network selection strategy based on system's perspective and evaluate the system performance of the proposed network selection strategies.

Another issue for IHWMNs is how to manage the resource for supporting multiple traffic like voice, video, and data. Resource management to support multiple traffic in an IHWMN is critical to the system performance. Although some resource management schemes have been proposed [18], [19], and [20] [21] [22], most of them focused on either multiple traffic in a single type of WMN or a single type of traffic in IHWMNs. Therefore, they may not be efficient to support multiple traffic in IHWMNs. Our motivation is to design efficient resource management schemes that can consider the heterogeneities of traffic and networks.

In this thesis, we propose several more realistic traffic models and system models for IHWMNs. Based on the proposed models, we tackle the network selection strategies and resource management schemes in IHWMNs. Firstly, we propose a cost-function-based network selection (CFNS) strategy. Unlike most existing user-centric network selection strategies, the proposed CFNS strategy is designed based on system's perspective. It also takes into account user's individual needs. The proposed CFNS strategy is analyzed by using theoretical model and extensive simulations. Secondly, we propose preemption-based resource management schemes to support voice and data traffic in IHWMNs. Furthermore, an algorithm is applied to achieve the best performance for data traffic while satisfying the guaranteed QoS requirement for voice traffic. Finally, we also propose two resource management schemes in IHWMNs from different perspectives. The first scheme, traffic-based resource management scheme (TRMS), allocates the system resource based on the traffic types. In the other scheme, Markov decision process is used to model the resource management scheme and a Q-learning-based resource management scheme (QRMS) is proposed to find the optimal resource management in IHWMNs.

1.5 Organization of the Thesis

The remainder of this thesis is organized as follows. Chapter 2 gives a brief introduction of the related work, which includes network selection strategies, handoff decision procedure and algorithms, and resource management in IHWMNs. In Chapter 3, traffic and system models for IHWMNs are proposed. Based on the proposed models, CFNS strategy is designed to select a desired network for mobile users. The theoretical analysis of the proposed CFNS strategy is verified by extensive simulations. Then, preemption-based resource management schemes to support voice and data traffic are proposed in Chapter 4. An algorithm is also designed to achieve

the best performances for data traffic while satisfying the guaranteed QoS requirements for voice traffic. Chapter 5 proposes two novel resource management schemes from different perspectives: TRMS and QRMS. Extensive simulations are conducted to compare the performance of the proposed schemes. Finally, we conclude the thesis and describe the potential topics in Chapter 6.

Chapter 2

Related Research

2.1 Introduction

This chapter gives a brief overview of the existing research that is related to IHWMNs (integrated heterogeneous wireless and networks). The first issue is how to combine different types of wireless and mobile networks (WMNs) together and let them cooperate with each other. An interworking mechanism is required so that a mobile user can roam across different types of WMNs seamlessly. The second issue is the network selection strategy. When an originating (or new) call arrives, a network selection strategy is required to select a desired network for the originating call. For an ongoing call, some vertical handoff decision algorithms are used to determine if it needs to switch to another network. If the active mobile user finds a more preferred network, the mobile user may request a vertical handoff and changing the connection to the more preferred network. The last but not least is the resource management scheme which allocates the resources for different WMNs to different types of traffic. A good resource management scheme can efficiently utilize the system resources and provide satisfied QoS for

mobile users.

This chapter is organized as follows. Different integration architectures are discussed in the next section. In Section 2.3, some existing network selection strategies are reviewed. Existing vertical handoff process and decision algorithms are presented in Section 2.4. Then, resource management issues are discussed in Section 2.5. Finally, we conclude this chapter in Section 2.6.

2.2 Interworking among Heterogeneous Wireless and Mobile Networks

Usually, existing WMNs have different physical transmission characteristics, signaling message formats, their own charging models, etc. An interworking mechanism needs to effectively combine them together. In [23], two different mechanisms, *tight coupling* and *loose coupling*, have been introduced to interconnect WLAN and GPRS networks. In the tight coupling mechanism, WLAN connects to the GPRS core network like other Radio Access Networks (RANs). In other words, the traffic between WLAN and other networks goes through the GPRS core network. Therefore, the traffic of WLAN incurs a burden to the GPRS core network. In loose coupling mechanism, however, WLAN is deployed as a complementary network for the GPRS network. The traffic of WLAN does not go through the GPRS core network. The tight coupling mechanism requires that WLAN and GPRS network belong to the same operator. By using loose coupling, the WLAN and GPRS can be deployed individually. Both networks need not belong to the same operator, which is more flexible than tight coupling. In [24], the authors have considered several different interworking scenarios between 3G networks and WLANs. Two scenarios, 3G-based access control, charging, and access to 3G packet-switched service, have been

discussed in details. Additionally, 3GPP (the third Generation Partnership Project) [25] also has discussed the requirements, principles, architectures, and protocols to interwork 3G networks and WLANs.

The authors in [26] have proposed another architecture and it is called architecture for ubiquitous mobile communications (AMC). Unlike the above interworking architectures, the AMC integrates heterogeneous WMNs by introducing a third party. The third party, named as network inter-operating agent (NIA), resides in the Internet and manages the users from different networks and service providers. It also handles the authentication, authorization, and billing when a mobile user is roaming across different types of WMNs in the AMC. Each WMN in the AMC, such as cdma2000 or GPRS, needs an additional function entity to communicate with the NIA. IP (Internet Protocol) is used as the interconnect protocol, which makes the various access technologies transparent to the applications. By using such architecture, the scalability is not a serious problem because the architecture can integrate many WMNs using the third party.

All the above interworking architectures only consider the interworking among centralized WMNs. However, IHWMN also can include wireless and mobile ad hoc networks. Therefore, more comprehensive and complex interworking architectures that include wireless and mobile ad hoc networks have been discussed in [27]. The state-of-art research in physical layer, data link layer, network layer, transport layer, and application layer have been presented. The authors also have discussed the open issues that are related to each layer in the entire integration architecture.

2.3 Network Selection

When a multi-mode terminal generates a call in an IHWMN, it requires a strategy to determine which network should be accessed. In [13], since a mobile user always selects the network

with the highest available bandwidth among all the available networks during its communication, the only concern of the network selection for the mobile user is bandwidth. From the user's point of view, this is good for the service quality. In [14], a network selection strategy that only considers the power consumption mobile users has been introduced. In order to maximize the battery life, the mobile user selects the uplink and downlink from 3G network or WLAN that have the lowest power consumption. Consider the scenario that the power consumption of the uplink in 3G network is less than the uplink in WLAN and the power consumption of the downlink in 3G network is larger than the downlink in WLAN. Using the network selection strategy in [14], the mobile user selects the uplink in 3G network and the downlink in WLAN to communicate simultaneously because this combination achieves the least power consumption. In [15], the authors have proposed a policy-enabled network selection strategy which combines several factors such as bandwidth provision, price, and power consumption. A mobile user defines the "best" network based on his preferences. By setting different weights over different factors, a mobile user can calculate the total cost of each available network. The mobile user connects to the network with the highest cost, which is its most desired network. In order to reduce the computation complexity of the cost function in [15], an optimization algorithms have been proposed in [16]. The authors have proposed another network selection algorithm in [17] by using two mathematic methods: analytical hierarchy process (AHP) and grey relational analysis (GRA). The AHP algorithm divides the complex network selection problem into a number of decision factors and the optimal solution can be found by integrating the relative dominance among these factors. The GRA [17] has also been proposed for selecting the best network for a mobile user. The network selection strategy discussed in [28] includes two interesting factors, network ability in covering user next locations and unreliability of a given access network. The network ability in covering user next locations indicates the probability that a mobile user stays

within a network after the next movement. A higher value of this factor implies wider coverage, which is preferred by the mobile user. The network unreliability is used to evaluate the QoS stability in a specific network. A network with a higher unreliability value may result in more QoS degradations even if it currently can provide more satisfied QoS. The network ability in covering user next locations depends on the specific predication algorithms, while the network unreliability is obtained from historical statistic data [28].

Although the above network selection strategies have their own advantages, they are all designed to meet individual mobile user's needs. That is, they are user-centric. Furthermore, they do not put much attention on the system performances, such as the blocking probability of originating calls and the forced termination probabilities of horizontal and vertical handoff calls.

In [29], a network selection scheme that considers both system and users' preference has been discussed. It can provide satisfied QoS to mobile users without degrading operator's profit. The profit of network operator is evaluated by long-term revenue and resource utilization. In their proposed scheme, the network selection is formulated as a Semi-Markov decision process. Q-learning, as a reinforcement learning method, is used to achieve the optimal policy. Only the forced termination probability of handoff calls is used to present the user's QoS. Microeconomic theory is also applied to solve network selection problem in [30] [31]. Utility function, as a very useful tool to evaluate the benefits obtained in the microeconomic theory, is also applied to select a network. In [30], different types of traffic are assumed to have different utility functions. For example, the utility of voice traffic does not increase even when a higher bandwidth is allocated, while the utility of data traffic increases significantly when a higher bandwidth is allocated. The network selection algorithm in [30] can maximize the total utilities of all the types of traffic in

each network. By applying microeconomic theory, the price of each network also can be adjusted to maximize the total utilities. The tradeoff between user's attitude to make a risk and their corresponding network selection rules has been discussed in [31]. Consumer surplus, defined as the difference between the money value of the data to the user and actual money cost paid by user in [31], has to be maximized. When the price increases, the delay experienced by a mobile user decreases. Therefore, the network selection algorithm is formulated to select a network that has the maximum consumer plus while meeting the transfer completion time.

The network selection strategies in [29] [30] focus on the systems performances. Their results have shown that the network selection strategies from system's perspective can achieve better system's performance than the user-centric strategies. However, they did not put much attention on users' needs.

2.4 Vertical Handoff

Vertical handoff attracts a lot of attention due to its importance in IHWMNs. Basically, a vertical handoff process consists of three phases: *network discovery phase*, *vertical handoff decision phase*, and *vertical handoff execution phase*. In the first phase, an active mobile user keeps searching its preferred network that can provide better service than the current serving network. The interfaces of the preferred networks can be activated all the time for the purpose of search. However, the power consumption is significant large, which reduces the battery life. Another strategy is to activate the interfaces of the preferred networks periodically. Obviously, the selection of the duration between two consecutive activation is very critical. If this duration is too small, the power consumption is still large. The mobile user may not find its preferred networks promptly if this duration is too large. In [12], the authors have proposed a strategy

to search the preferred networks promptly while saving unnecessary power consumption. In their strategy, the location information of the mobile user and the preferred networks can be obtained from a Location-Service Server [12]. When the active mobile user reaches an area that is covered by a preferred network, its associated interface is activated to search the beacon signal from the preferred network. Another strategy using pattern recognition technique has been proposed in [32]. By dividing all the walking paths into small segments, the pattern recognition technique is applied to find a suitable vertical handoff position, which effectively alleviates the ping-pong effect. In order to reserve resources for incoming vertical handoff requests, a location prediction strategy has been proposed in [33] to predict the potential vertical handoff. Time of arrival (TOA) and angle of arrival (AoA) based positioning techniques are used to determine the current positions of the mobile users. By obtaining the positions at different sampling times, the direction where the mobile user is moving forward can be predicted. As a result, the resources are reserved in the network where a potential vertical handoff happens. Different sampling durations are required for different size of network to achieve the optimal system performance.

The second phase in the vertical handoff process is handoff decision. Since the vertical handoff may not be mandatory and it incurs significant signaling messages, the decision algorithm is critical to the IHWMN. The vertical handoff decision is also seen as network selection problem in some literature [15] [17]. A vertical handoff decision algorithm using intelligent technology has been designed in [34]. The number of users in a WMN after a successful vertical handoff is considered to affect the QoS of the IHWMN. A modified Elman neural network is used to predict such number. The predicted number of mobile users is fed into a fuzzy interference system to make a vertical handoff decision. Except the number of users after handoff [34], the bandwidth required by each traffic and the velocity of mobile users are also fed into the fuzzy decision system. Other strategies using fuzzy techniques can be found in [35]. In [36], the authors

have compared several vertical handoff decision algorithms. The compared algorithms include multiplicative exponent weighting (MEW) [35], simple additive weighting (SAW) [35], technique for order preference by similarity to ideal solution (TOPSIS) [35], and GRA in [17]. Four types of traffic have been examined in their comparisons, which are conversational, streaming, interactive, and background. Their results showed that the MEW, SAW, and TOPSIS achieve similar performances in bandwidth, delay, jitter, and bit error rate. The performance of GRA is slight higher than other three algorithms in bandwidth and delay for interactive and background traffic.

In [37], a evaluation framework for vertical handoff decision in an IHWMN has been introduced. Four metrics are used for performance evaluation, which include the number of unnecessary vertical handoff, WLAN utilization, user's bandwidth, and user's packet delay. In [38], a utility function has been proposed to evaluate the satisfaction degree of mobile user. That is, the vertical handoff decision has to maximize the expected total utility. The assumption in [38] is that the location information of each mobile user and its surrounded high bandwidth networks is available. The vertical handoff process can only be made at some discrete time units. As a result, the handoff process can be formulated as a Markov decision process, where the handoff decision can be obtained by using dynamic programming technique.

In the final phase of a vertical handoff process, the signaling message and incoming traffic are directed to another network. Therefore, the handoff execution includes radio link transfer and context transfer [39]. Some design rules also have been discussed for the radio link transfer and context transfer in [39]. For the radio link transfer, the signaling message comes from different types of networks must be formatted for interpretation in the new network. QoS negotiation is also required in the new network since the variation of the service quality may happen when

making a vertical handoff. Context transfer, including state information in the original network, has to be delivered to the new network to reduce the handoff delay [39].

Although the above schemes achieve some advantages during the whole vertical handoff process, most of them do not consider the forced termination probability of handoff calls. Assume an active mobile user makes a DVH (downward vertical handoff) to a network with better service. When the mobile user moves out its coverage, a failed UVH (upward vertical handoff) incurs communication disruption which should be avoided. However, they do not consider such effect and assume successful UVH. In our resource management schemes, a failed UVH causes the communication interrupt and needs to be avoided.

2.5 Resource Management

In [40], the authors have presented different call admission control policies for voice and data traffic. Since data traffic is delay-insensitive and voice traffic is stringent to access delay, they have proposed to allow voice traffic to preempt data traffic. A priority queue is introduced to hold the preempted data calls [40]. When a data call arrives, it is also put into the queue if there is no enough resource. Although their scheme improves the blocking probability of originating voice calls, it treats the originating calls and the handoff calls equally. Since terminating an ongoing call is more frustrating than blocking an originating call from a user's point of view, higher priority should be provided to the ongoing calls (handoff calls).

In [41], the authors have proposed an analytical model that supports preemptive and priority reservation for handoff calls. Detailed performance analysis is also provided to give guidelines on how to config system parameters to balance the blocking probability of originating calls and the forced termination probability of handoff calls. Multiple traffic with different QoS

requirements have been discussed in [42]. In order to support different types of traffic, a model that gives different priorities to different types of traffic has been designed. Their model allows the traffic with lower priority to be preempted by the traffic with higher priority, which can support DiffServ (Differentiate Service) in WMNs [42]. Each type of traffic has a queue to hold the same type of preempted calls. When a new call is generated, it is also put into the queue when there is no free channel available. The calls in the queue can be served when the resource becomes available in the order of priority. In other words, the available resource is first allocated to the call that has the highest priority [42]. More resource management schemes also can be found in [18], [19], and [20]. Although all of the above resource management schemes achieve significant improvements on the system performances, they focus on a single WMN, which may not efficiently support multiple traffic in an IHWMN.

Compared to a single type of WMN, the resource management in an IHWMN has to face more challenges due to the heterogeneity of different types of WMNs. That is, different types of WMNs may have different resource management policies for the same type of traffic. The resource management scheme in [43] treats the real-time and non-real-time traffic differently in an integrated CDMA-WLAN network. For real-time traffic, vertical handoff is made as soon as possible to minimize the handoff delay. For non-real-time traffic, they considered that the amount of data being transmitted is more important than the delay. Therefore, the connection to the higher bandwidth network is kept as long as possible to maximize the throughput. In [44], the authors have also proposed different vertical handoff policies for real-time and non-real-time traffic like [43]. Although all of the above schemes improve the system performances in certain perspectives, call-level performances such as the blocking probability of originating calls and the forced termination probability of handoff calls are not examined. Furthermore, in all of above schemes, any type of traffic is switched to a higher bandwidth network when a higher bandwidth

network becomes available. However, this policy may not be suitable for some delay-sensitive traffic because frequent handoffs may interrupt the ongoing communications.

In [21], the mobile terminal has a preference to connect to different types of networks. Such preference triggers the vertical handoff when a preferred network becomes available. Traditional resource allocation, called disjoint resource allocation in [21], allocates the resource in each network individually. Therefore, using traditional resource allocation, a mobile user is rejected if its preferred network is congested. However, in joint resource allocation, a call blocked by its preferred network still can be accepted by another available network. The blocking probability of originating calls is much better and the forced termination probability of handoff calls is slight worse if using the joint resource allocation. In [22], another joint session admission control strategy has been proposed for an integrated CDMA-WLAN network. The admission control algorithm is formulated as an optimization problem under multiple constraints. That is, the optimal admission control algorithm has to maximize the total revenue for the integrated CDMA-WLAN network, while satisfying multiple QoS requirements such as the blocking probability of originating calls and the forced termination probability of handoff calls in WLAN or CDMA network. By using semi-Markov decision process, the optimum joint admission control algorithm can be solved using linear programming technique. The goal of the proposed resource management scheme in [45] is to increase user's data rate and decrease the blocking probability and the forced termination probability. A switch profit is used to encourage the vertical handoff to the network that can offer better bandwidth. On the other hand, a handoff cost is used to prevent excessive vertical handoff. The switch profit depends on the bandwidth gain obtained from the vertical handoff, while the handoff cost depends on the delay incurred by the vertical handoff. The simulation results show that their scheme can reduce the blocking probability and the forced termination probability. It also achieve better throughput and grade

of service [45]. In [46], the bandwidth allocated to the mobile user is not fixed, while depending on the bandwidth availability. If there is not enough bandwidth to satisfy the basic bandwidth requirements, the bandwidth adaption process is executed to remove some bandwidth from active mobile users whose allocated bandwidth is larger than the basic bandwidth requirement. The system tries to make some active users vertically hand over to other networks to release the requested bandwidth. An interesting function, defined as willingness function, is used to evaluate the degree that an active mobile user wants to make a vertical handoff. An active mobile user, which is allocated less bandwidth, has a larger willingness value. That is, it is more likely to be vertically switched to other networks with more sufficient bandwidth. It is obvious that the scheme achieves better performance since the capacity increases in the system. However, the performance of a scheme that a vertical handoff is made before bandwidth adaption is not examined.

A framework to support high bandwidth real-time traffic through multiple wireless interfaces has been discussed in [47]. Due to high bandwidth requirements, some real-time traffic such as video has to split their bandwidth demands and requests bandwidth from different types of WMNs. On the other hand, delay-sensitivity of real-time traffic imposes great challenge for such splitting scheme. The authors in [47] have proposed an efficient scheduling algorithm to support such implementation to use multiple interfaces simultaneously. Their scheme also provides an interesting open topic, which is how to allocate the requested bandwidth among multiple WMNs.

The above resource management schemes allocate the resources in different types of WMNs to the mobile users from system's perspective. However, less work has focused on the multiple traffic. In this thesis, we propose several resource management schemes to support multiple

traffic in IHWMNs.

2.6 Summary

In this chapter, several integration architectures to combine heterogeneous WMNs were introduced. We also described different network selection strategies, either user-centric or system-centric. Vertical handoff process which can be divided into three phases was also explained. Finally, how to allocate the resource in different types of WMNs was discussed. In the next chapter, we propose a CFNS (cost-function-based network selection) strategy in an IHWMN and analyze its system performances.

Chapter 3

Cost-Function-based Network Selection Strategy

3.1 Introduction

Network selection strategy is critical to the performances of the IHWMNs. However, most existing network selection strategies are user-centric. Furthermore, the system performance has not been touched. In this chapter, we will propose and analyze a CFNS (cost-function-based network selection) strategy in IHWMNs. The proposed network selection strategy is designed from the system's perspective. It also consider users' needs.

In the next section, we introduce our proposed system model for an IHWMN. In Section 3.3, a CFNS strategy is presented. Section 3.4 analyzes the performance of the proposed CFNS strategy using theoretical method. Section 3.5 provides the performance evaluation of the system through theoretical analysis and simulations. Finally, we conclude this chapter in Section 3.6.

3.2 System Model

We consider an integrated heterogeneous wireless and mobile system having M different types of networks. We assume that the entire service area of the system is covered by network N_1 that consists of many homogeneous cells and provides a low bandwidth service. Assume that network N_i ($2 \leq i \leq M$) is randomly distributed in the service area covered by network N_1 and provides a higher bandwidth service than network N_1 . Network N_i ($2 \leq i \leq M$) has limited coverage, which only covers some portion of the entire service area. For example, a cellular network (N_1) covers several WLANs ($N_2, N_3, \dots, N_M$). For the purpose of simplicity, we focus on one cell of network N_1 , which is called *marked cell*, where some area is covered by several high bandwidth networks as shown in Figure 3.1. Each cell of a higher bandwidth network N_i ($2 \leq i \leq M$) has an AP (access point), and each cell of network N_1 has a BS (base station).

Figure 3.1: Coverage of different types of networks

We assume that each cell of network N_i ($1 \leq i \leq M$) has a circular cell shape with radius

R_i . We define the area covered by network N_i ($1 \leq i \leq M$) as area A_i ($1 \leq i \leq M$). The area in the marked cell that is only covered by network N_1 is defined as area A_s , which indicates it is covered only by a single network. In the overlapped areas, mobile users may have more than one connection option. For example, in Figure 3.1, a mobile user in area A_3 can connect to networks N_1 and N_3 if both networks have free bandwidth. We assume that each cell of network N_i ($1 \leq i \leq M$) has B_i bandwidth units. It is necessary to clarify that each bandwidth unit is a logic channel which can be allocated to a mobile user.

We assume that mobile users are uniformly distributed in the service area. They move in all the directions with equal probability. The moving speed V (random variable) of mobile user follows an arbitrary distribution with a mean value of $E[V]$. In the system, we assume that there are three types of calls, namely *originating calls*, *horizontal handoff calls*, and *vertical handoff calls*. An originating call is an initial call in the system, and a handoff call, either horizontal or vertical handoff call, is an ongoing call. When an active mobile user changes its connection from its current serving network N_i to network N_j (for all i, j), a handoff call (request) is generated in network N_j . If $i = j$, the handoff call is a horizontal handoff call. If $i \neq j$, it is a vertical handoff call.

3.3 Network Selection Strategy

As we introduced in Section 2.3, most existing network selection strategies are user-centric and focus on the individual user's needs. Our motivation is to design a network selection strategy from system's perspective and the network selection strategy can also meet certain individual user's needs. In the following, we discuss how our proposed network selection strategy works.

When an originating call is generated, the proposed network selection strategy works as

follows.

- If there is no free bandwidth unit, the originating call is blocked;
- If only one available network has free bandwidth units, the originating call is accepted by that network;
- If there are more than one available network having free bandwidth units, all these candidate networks are compared based on network selection strategy and the originating call is accepted by the most desired network.

Since we focus on network selection strategy in this paper, horizontal handoff is handled in a traditional way like [48] and vertical handoff is handled in the following ways: when an active mobile user moves from area A_i into adjacent area A_j ($i \neq j$), it changes its connection from network N_i to N_j if network N_j has a higher bandwidth than N_i and there are free bandwidth units in N_j . If area A_j is not covered by network N_i , the mobile user has to change its connection to other available networks. If there is no free bandwidth unit in other available networks, the vertical handoff call will be forcedly terminated. If there are more than one available network having free bandwidth units, the vertical handoff call is randomly accepted by any one of these networks.

Our proposed network selection strategy prefers an originating call to be accepted by a network with a low traffic load and stronger received signal strength, which can achieve better traffic balance among different types of networks and a good service quality. Consequently, we define a cost function to combine these two factors, traffic load and received signal strength. Therefore, the cost to use network N_i for an originating call is defined as

$$C_i = w_g \cdot G_i + w_s \cdot S_i, \text{ for } i = 1, 2, \dots, M, \quad (3.1)$$

where G_i is the complementary of normalized utilization of network N_i . S_i is the relative received signal strength from network N_i . w_g ($0 \leq w_g \leq 1$) and w_s ($0 \leq w_s \leq 1$) are the weights that provide preferences to G_i and S_i , respectively. The constraint between w_g and w_s is given by

$$w_g + w_s = 1. \quad (3.2)$$

The complementary of normalized utilization G_i is defined by

$$G_i = \frac{B_{if}}{B_i}, \text{ for } i = 1, 2, \dots, M, \quad (3.3)$$

where B_{if} is the available bandwidth units of network N_i and B_i is the total bandwidth units of network N_i . In general, stronger received signal strength indicates better signal quality. Therefore, an originating call prefers to be accepted by a network with a higher received signal strength. However, it is difficult to compare received signal strengths among different types of networks because they have different maximum transmission powers and receiver threshold. As a result, we propose to use a relative received signal strength to compare different types of WMNs. S_i in Equation (3.1) is defined by

$$S_i = \frac{P_i^c - P_i^{th}}{P_i^{max} - P_i^{th}}, \text{ for } i = 1, 2, \dots, M, \quad (3.4)$$

where P_i^c is the current received signal strength from network N_i . P_i^{th} is the receiver threshold from network N_i . P_i^{max} is the maximum transmitted signal strength from network N_i . Note that we only consider path loss in the propagation model. Consequently, the received signal strength (in decibel) from network N_i is given by

$$P_i^c = P_i^{max} - 10\gamma \log(r_i), \quad (3.5)$$

where r_i is the distance between the mobile user and the BS (or AP) of network N_i , and γ is the fading factor that is generally in the range of $[2, 6]$. Therefore, the receiver threshold from

network N_i is given by

$$P_i^{th} = P_i^{max} - 10\gamma \log(R_i). \quad (3.6)$$

The relative received signal strength from network N_i is rewritten as

$$S_i = 1 - \frac{\log(r_i)}{\log(R_i)}, \text{ for } i = 1, 2, \dots, M. \quad (3.7)$$

If an originating call has more than one connection option, the costs for all candidate networks are calculated by using cost function of Equation (3.1). The originating call is accepted by a network that has the largest cost, which indicates the “best” network. If there are more than one “best” network, the originating call is randomly accepted by any one of these “best” networks.

In the following, we discuss two special cases of the proposed CFNS strategy, i.e., $w_g = 1$ and $w_g = 0$. When $w_g = 1$, the cost function of Equation (3.1) only considers G_i . It gives rise to another network selection strategy and we call it traffic balanced-based network selection (TBNS) strategy. This network selection strategy tries to achieve the best traffic balance among different types of networks. In this case, when an originating call is generated and there are more than one network having free bandwidth units, the originating call is accepted by a network that has the largest G_i . That is, the call is accepted by a network which has more free bandwidth units. In the second case, when $w_g = 0$, the proposed CFNS strategy gives rise to another network selection strategy, i.e., received signal strength-based network selection (RSNS) strategy. It is obvious that the only concern of selecting a desired network is based on received signal quality. In this case, when an originating call is generated in an area covered by more than one network, the call is accepted by the network that has the largest S_i .

In this thesis, although our cost function only consists of two factors, traffic load and received signal strength, it is easy to extend to involve more factors like access fee of using network N_i ,

which can be rewritten as

$$C_i = w_g \cdot G_i + w_s \cdot S_i + w_\phi \cdot \Phi_i, \quad (3.8)$$

and access fee Φ_i is given by

$$\Phi_i = 1 - \frac{\phi_i}{\phi_{max}}, \quad (3.9)$$

where ϕ_{max} is the highest access fee that the mobile user likes to pay and ϕ_i is the actual access fee to use network N_i . The mobile user does not connect to a network which charges more than ϕ_{max} even if the network has free bandwidth units. w_ϕ ($0 \leq w_\phi \leq 1$) is the weight for the access fee with the constraint

$$w_g + w_s + w_\phi = 1. \quad (3.10)$$

Therefore, a network with a cheaper price has a larger cost, and the mobile user is more likely to be accepted by that network. Using the similar way, other factors also can be included into the cost function after properly normalization.

3.4 Analysis

In this section, we analyze the performance of the system that uses the proposed CFNS strategy by theoretical model. The blocking probability of originating calls and the forced termination probability of handoff calls are two major performance metrics. We assume that there are $M - 1$ higher bandwidth networks and these higher bandwidth networks cover some portions of the marked cell. In order to simplify the analysis, we also assume that each higher bandwidth network only has one cell in the marked cell and these higher bandwidth networks do not overlap with each other. That is, areas A_i ($2 \leq i \leq M$) and A_j ($2 \leq j \leq M$) do not overlap with each other if $i \neq j$. We also assume that area A_i ($2 \leq i \leq M$) does not cross

the boundary of the marked cell. In the following, we first introduce a traffic model and then analyze the system performance by using Markov model.

3.4.1 Network Selection Probability

The location of a mobile user in area A_i ($2 \leq i \leq M$) can be presented by $[r_i \cos(\alpha) + x_i, r_i \sin(\alpha) + y_i]$ ($2 \leq i \leq M$), where α is the relative angle of the mobile user to the center of network N_i , and (x_i, y_i) is the location of the center of network N_i ($2 \leq i \leq M$). As a result, the distance r_1 between the mobile user and center of the marked cell of network N_1 is given by

$$r_1 = \sqrt{[r_i \cos(\alpha) + x_i - x_1]^2 + [r_i \sin(\alpha) + y_i - y_1]^2}, \quad 2 \leq i \leq M, \quad (3.11)$$

where (x_1, y_1) is the location of the center of the marked cell in network N_1 . By setting $(x_1 = 0, y_1 = 0)$, r_1 is rewritten as

$$r_1 = \sqrt{[r_i \cos(\alpha) + x_i]^2 + [r_i \sin(\alpha) + y_i]^2}. \quad (3.12)$$

Since we assume that users are uniformly distributed in the service area, the probability density function (pdf) of r_i ($2 \leq i \leq M$) is given by

$$f(r_i) = \frac{2r_i}{R_i^2}, \quad 0 \leq r_i \leq R_i. \quad (3.13)$$

The pdf of α is given by

$$f(\alpha) = \frac{1}{2\pi}, \quad 0 \leq \alpha < 2\pi. \quad (3.14)$$

Consequently, the probability that the cost of network N_1 which is larger than that of N_i ($2 \leq i \leq M$) is given by

$$P(C_1 > C_i) = P \left\{ \left[w_g \cdot \frac{B_{1f}}{B_1} + w_s \cdot \frac{\log(\frac{R_1}{r_1})}{\log(R_1)} \right] > \left[w_g \cdot \frac{B_{if}}{B_i} + w_s \cdot \frac{\log(\frac{R_i}{r_i})}{\log(R_i)} \right] \right\}. \quad (3.15)$$

3.4.2 Traffic Model

A. Dwell Time of a Mobile User

The dwell time $T_{A_{so}}$ (random variable) of a mobile user is defined as the duration that a mobile user stays in area A_s before it moves out of the boundary of the marked cell. In order to obtain $T_{A_{so}}$, we adapt the fluid flow model [49] [50]. A two-dimensional fluid flow model assumes that the mobile users are uniformly distributed throughout the area and each mobile user moves in any direction with equal probability. Therefore, the average outgoing rate μ_{A_s} of area A_s is given by

$$\mu_{A_s} = \frac{E[V]L_{A_s}}{\pi A_{A_s}}, \quad (3.16)$$

where A_{A_s} is the area of A_s , L_{A_s} is the length of perimeter of A_s , and $E[V]$ is the average of the moving speed V (random variable) of mobile users. The radius of network N_i ($1 \leq i \leq M$) is defined as R_i . Then, A_{A_s} is given by

$$A_{A_s} = A_{A_1} - \sum_{i=2}^M A_{A_i}, \quad (3.17)$$

where A_{A_i} ($1 \leq i \leq M$) is the area of A_i and is given by

$$A_{A_i} = \pi R_i^2, \text{ for } 1 \leq i \leq M. \quad (3.18)$$

The perimeter of area A_s consists of the cell boundary of the marked cell and boundaries between A_s and A_i for all $2 \leq i \leq M$. Therefore, L_{A_s} in Equation (3.16) is given by

$$L_{A_s} = L_{A_{so}} + \sum_{i=2}^M L_{A_{si}}, \quad (3.19)$$

where $L_{A_{so}}$ is the length of the marked cell boundary, and $L_{A_{si}}$ is the length of the boundary between A_s and A_i ($2 \leq i \leq M$). $L_{A_{so}}$ is given by

$$L_{A_{so}} = 2\pi R_1, \quad (3.20)$$

and $L_{A_{si}}$ ($2 \leq i \leq M$) is given by

$$L_{A_{si}} = 2\pi R_i, \text{ for } 2 \leq i \leq M. \quad (3.21)$$

Consider an active mobile user in area A_s . When it moves out of area A_s before call completion, it may move out of the marked cell, or move into other area A_i ($2 \leq i \leq M$) which is covered by network N_1 and N_i ($2 \leq i \leq M$). Therefore, A_s outgoing mobile users consist of the mobile users out of the marked cell and the mobile users moving into other areas A_i ($2 \leq i \leq M$) in the marked cell, we decompose μ_{A_s} as cell outgoing rate $\mu_{A_{so}}$ and A_{si} ($2 \leq i \leq M$) outgoing rate $\mu_{A_{si}}$, which is given by

$$\mu_{A_s} = \mu_{A_{so}} + \sum_{i=2}^M \mu_{A_{si}}. \quad (3.22)$$

Therefore, the cell outgoing rate $\mu_{A_{so}}$ is given by

$$\begin{aligned} \mu_{A_{so}} &= \mu_{A_s} \cdot \frac{L_{A_{so}}}{L_{A_{so}} + \sum_{i=2}^M L_{A_{si}}} \\ &= \frac{E[V]L_{A_{so}}}{\pi A_{A_s}}. \end{aligned} \quad (3.23)$$

Similarly, the outgoing rate $\mu_{A_{si}}$ ($2 \leq i \leq M$) from area A_s to A_i is given by

$$\mu_{A_{si}} = \frac{E[V]L_{A_{si}}}{\pi A_{A_s}}, \text{ for } 2 \leq i \leq M. \quad (3.24)$$

Thus, the dwell time $T_{A_{so}}$ has a mean value of $1/\mu_{A_{so}}$, which can be obtained by

$$\begin{aligned} E[T_{A_{so}}] &= \frac{1}{\mu_{A_{so}}} \\ &= \frac{\pi A_{A_s}}{E[V]L_{A_{so}}}. \end{aligned} \quad (3.25)$$

Similarly, the dwell time $T_{A_{si}}$ ($2 \leq i \leq M$) (random variable) is defined as the duration that a mobile user stays in area A_s before moving into A_i ($2 \leq i \leq M$). The mean of $T_{A_{si}}$ is equal to $1/\mu_{A_{si}}$, which can be obtained by

$$\begin{aligned} E[T_{A_{si}}] &= \frac{1}{\mu_{A_{si}}} \\ &= \frac{\pi A_{A_s}}{E[V]L_{A_{si}}}, \text{ for } 2 \leq i \leq M. \end{aligned} \quad (3.26)$$

The dwell time T_{A_i} ($2 \leq i \leq M$) (random variable) is defined as the duration that a mobile user stays in area A_i before it moves out of A_i . According to fluid flow model, the average outgoing rate μ_{A_i} ($2 \leq i \leq M$) of mobile users in area A_i is given by

$$\mu_{A_i} = \frac{E[V]L_{A_{si}}}{\pi A_{A_i}}, \text{ for } 2 \leq i \leq M. \quad (3.27)$$

T_{A_i} has a mean value of $1/\mu_{A_i}$, which is obtained by

$$\begin{aligned} E[T_{A_i}] &= \frac{1}{\mu_{A_i}} \\ &= \frac{\pi A_{A_i}}{E[V]L_{A_{si}}}, \text{ for } 2 \leq i \leq M. \end{aligned} \quad (3.28)$$

B. Arrival Rates of Calls

We assume that the average arrival rate of originating calls in the marked cell of network N_1 is λ_O . Because the users are uniformly distributed in the marked cell, the average arrival rate of originating calls in area A_s is given by

$$\lambda_{OA_s} = \frac{A_{A_s}}{A_1} \cdot \lambda_O. \quad (3.29)$$

Similarly, the average arrival rate of originating calls in area A_i ($2 \leq i \leq M$) is given by

$$\lambda_{OA_i} = \frac{A_{A_i}}{A_1} \cdot \lambda_O, \text{ for } 2 \leq i \leq M. \quad (3.30)$$

We define the average number of active mobile users in area A_s as $E[U_{A_s}]$. As a result, the average rate of mobile users moving out of the marked cell without completing their communications can be expressed by $E[U_{A_s}]\mu_{A_{so}}$. Since network N_1 is assumed to have homogeneous cells, the average arrival rate λ_{HH} of horizontal handoff calls of the marked cell is equal to the average rate of mobile users moving out of the marked cell without completing their communications, which is given by

$$\lambda_{HH} = E[U_{A_s}]\mu_{A_{so}}. \quad (3.31)$$

When an active mobile user moves from area A_s to A_i ($2 \leq i \leq M$), it requests a vertical handoff to network N_i . Therefore, the average vertical handoff arrival rate to network N_i ($2 \leq i \leq M$) is given by

$$\lambda_{VH_i} = E[U_{A_s}] \mu_{A_{si}}, \text{ for } 2 \leq i \leq M. \quad (3.32)$$

We define the average number of active mobile users of network N_i as $E[U_{N_i}]$. The average rate of these mobile users moving out of area A_i ($2 \leq i \leq M$) without completing their communications can be expressed by $E[U_{N_i}] \mu_{A_i}$ ($2 \leq i \leq M$), which is also the average arrival rate of vertical handoff from network N_i ($2 \leq i \leq M$) to N_1 . Therefore, the average vertical handoff arrival rate to network N_1 is given by

$$\lambda_{VH_1} = \sum_{i=2}^M E[U_{N_i}] \mu_{A_i}. \quad (3.33)$$

C. Channel Holding Time

The call holding time T_c (random variable) is assumed to have a mean value $1/\mu_c$ and we have

$$E[T_c] = \frac{1}{\mu_c}. \quad (3.34)$$

We consider an active mobile user in network N_i ($2 \leq i \leq M$). When the mobile user finishes the communication before leaving area A_i ($2 \leq i \leq M$), or moves out of A_i before completing the communication, the current occupied channel is released. Therefore, the channel holding time T_{hA_i} ($2 \leq i \leq M$) (random variable) of network N_i ($2 \leq i \leq M$) is equal to the smaller one between the call holding time T_c of a mobile user and the dwell time T_{A_i} ($2 \leq i \leq M$). Since it has been proved that the assumption of exponential distribution is reasonable for the call holding time and cell dwell time by some field data [51], we assume that the call holding time of mobile users and the dwell time of N_i ($2 \leq i \leq M$) follow exponential distributions in

this thesis. Therefore, the channel holding time of network N_i ($2 \leq i \leq M$) is also exponentially distributed with a mean value as

$$\begin{aligned}
E[T_{hA_i}] &= \frac{1}{\mu_{hA_i}} \\
&= E[\min(T_{A_i}, T_c)] \\
&= \frac{1}{\mu_{A_i} + \mu_c}, \text{ for } 2 \leq i \leq M.
\end{aligned} \tag{3.35}$$

Next, we consider the channel holding time T_{hA_s} (random variable) in area A_s . An active mobile user may move out of cell boundary or move into area A_i ($2 \leq i \leq M$) before completing its communication, or completes its communication before moving out of area A_s . We assume that $T_{A_{so}}$ and $T_{A_{si}}$ ($2 \leq i \leq M$) also follow exponential distributions. Therefore, T_{hA_s} is also exponentially distributed with a mean value as

$$\begin{aligned}
E[T_{hA_s}] &= \frac{1}{\mu_{hA_s}} \\
&= E[\min(T_{A_{so}}, T_{A_{s2}}, \dots, T_{A_{sM}}, T_c)] \\
&= \frac{1}{\mu_{A_{so}} + \sum_{i=2}^M \mu_{A_{si}} + \mu_c}.
\end{aligned} \tag{3.36}$$

3.4.3 Markov Method

Since it is reasonable to assume Poisson process for originating and handoff arrival in [52], we assume that the arrival processes of originating calls and handoff calls are Poisson processes. From the above assumptions, we can use a $(2M - 1)$ -dimensional Markov chain to model the marked cell. In the following, we describe the system states and events of the Markov chain.

A. System States and Events

We define the state of the marked cell by $(2M - 1)$ -tuple nonnegative integers $(l_1, l_2, h_2, l_3, h_3, \dots, l_M, h_M)$, where l_1 is the sum of the occupied bandwidth units of network N_1 in area A_s . l_i ($2 \leq i \leq M$)

is the sum of the occupied bandwidth units of network N_1 in area A_i , and h_i ($2 \leq i \leq M$) is the sum of the occupied bandwidth units of network N_i ($2 \leq i \leq M$). Obviously, there are total $\sum_{i=1}^M l_i$ occupied bandwidth units of network N_1 and $l_i + h_i$ ($2 \leq i \leq M$) active mobile users in area A_i ($2 \leq i \leq M$). In the following analysis, we use x to denote the system state. That is, $x = (l_1, l_2, h_2, l_3, h_3, \dots, l_M, h_M)$. The permissible state space χ is given by

$$\chi = \left\{ x \mid \sum_{k=1}^M l_k \leq B_1 \cap h_i \leq B_i, \text{ for } 2 \leq i \leq M \right\}. \quad (3.37)$$

The state transitions are driven by events which include:

- *Event (a)*: Arrival of an originating call in area A_s or an arrival of horizontal handoff call;
- *Event (b)*: Call completion in area A_s or moving out of the marked cell;
- *Event (c)*: Arrival of an originating call in area A_i ($2 \leq i \leq M$);
- *Event (d)*: Call completion in area A_i ($2 \leq i \leq M$);
- *Event (e)*: An active mobile user moving from area A_s to A_i ($2 \leq i \leq M$);
- *Event (f)*: An active mobile user moving from area A_i ($2 \leq i \leq M$) to A_s ;

It has to be noted that not all the events result in deterministic state transitions. For example, when an originating call arrives in area A_s , the state changes if there are free bandwidth units in network N_1 . It means that the originating call can be accepted. On the other hand, the state does not change if there is no free bandwidth unit in network N_1 .

B. State Transitions

Figure 3.2 illustrates possible state transitions which are driven by the above events in state x . In the following analysis, we consider that current system state x is in $(l_1, l_2, h_2, \dots, l_M, h_M)$.

Figure 3.2: State transition diagram

It is to note that state x is a valid state that is in the permissible state space χ . The state transitions are analyzed event by event. Λ and Ψ are used to denote the transition rate from/to current state x .

For *Event (a)*, when an originating call is generated in area A_s or a horizontal handoff call arrives into area A_s from a neighboring cell, it is accepted by network N_1 if there are free bandwidth units in network N_1 . That is, the state transits from current state x to state $(l_1 + 1, \dots, l_i, h_i, \dots, l_M, h_M)$ only when $\sum_{k=1}^M l_k < B_1$. The transition rate Λ_a (i.e., $\Lambda_{Event(a)}$) is the total arrival rates of originating calls in area A_s and horizontal handoff calls, which is given by

$$\Lambda_a = \lambda_{OA_s} + \lambda_{HH}, \text{ if } \sum_{k=1}^M l_k < B_1. \quad (3.38)$$

If there is no free bandwidth unit in network N_1 , the state does not change which indicates that the call is blocked or forcedly terminated. There is also a state transition from state $(l_1 - 1, \dots, l_i, h_i, \dots, l_M, h_M)$ to current state x due to *Event (a)* and the transition rate Ψ_a is given by

$$\Psi_a = \lambda_{OA_s} + \lambda_{HH}, \text{ if } l_1 > 0. \quad (3.39)$$

For *Event (b)*, when an active mobile user completes its communication in area A_s or moves out of the marked cell of network N_1 before the call completion, the state transits from current

state x to state $(l_1 - 1, l_2, h_2, \dots, l_M, h_M)$. Since the average cell outgoing rate of mobile users is $l_1 \mu_{A_{so}}$ and the call completion rate is $l_1 \mu_c$, the transition rate Λ_b from current state x to state $(l_1 - 1, l_2, h_2, \dots, l_M, h_M)$ due to *Event (b)* is given by

$$\Lambda_b = l_1 \cdot (\mu_c + \mu_{A_{so}}), \text{ if } l_1 > 0. \quad (3.40)$$

Similarly, the state also transits from $(l_1 + 1, \dots, l_i, h_i, \dots, l_M, h_M)$ to current state x due to *Event (b)* and the transition rate Ψ_b is given by

$$\Psi_b = (l_1 + 1) \cdot (\mu_c + \mu_{A_{so}}), \text{ if } \sum_{i=1}^M l_i < B_1. \quad (3.41)$$

For *Event (c)*, when an originating call is generated in area A_i ($2 \leq i \leq M$), there are two possible state transitions, which correspond to the call acceptance to network N_1 or network N_i ($2 \leq i \leq M$), respectively. The call is accepted by the network based on the proposed CFNS strategy. Therefore, the transition rate Λ_c^{i1} from current state x to state $(l_1, \dots, l_i + 1, h_i, \dots, l_M, h_M)$ is given by

$$\Lambda_c^{i1} = \begin{cases} \lambda_{OA_i}, & \text{if } h_i = B_i \text{ and } \sum_{k=1}^M l_k < B_1, \\ P(C_1 > C_i) \cdot \lambda_{OA_i}, & \text{if } h_i < B_i \text{ and } \sum_{k=1}^M l_k < B_1, \end{cases} \quad (3.42)$$

where $P(C_1 > C_i)$ is the network selection probability that the cost of network N_1 is larger than that of network N_i ($2 \leq i \leq M$). On the other hand, the transition rate Λ_c^{i2} from current state x to state $(l_1, \dots, l_i, h_i + 1, \dots, l_M, h_M)$ is given by

$$\Lambda_c^{i2} = \begin{cases} \lambda_{OA_i}, & \text{if } h_i < B_i \text{ and } \sum_{k=1}^M l_k = B_1, \\ [1 - P(C_1 > C_i)] \cdot \lambda_{OA_i} & \text{if } h_i < B_i \text{ and } \sum_{k=1}^M l_k < B_1. \end{cases} \quad (3.43)$$

Similarly, the state transits from state $(l_1, \dots, l_i - 1, h_i, \dots, l_M, h_M)$ or $(l_1, \dots, l_i, h_i - 1, \dots, l_M, h_M)$ to current state x due to *Event (c)*. The transition rate Ψ_c^{i1} from state $(l_1, \dots, l_i - 1, h_i, \dots, l_M, h_M)$

to current state x is given by

$$\Psi_c^{i1} = \begin{cases} \lambda_{OA_i}, & \text{if } h_i = B_i \text{ and } l_i > 0, \\ P(C_1 > C_i) \cdot \lambda_{OA_i}, & \text{if } h_i < B_i \text{ and } l_i > 0, \end{cases} \quad (3.44)$$

and the transition rate Ψ_c^{i2} from state $(l_1, \dots, l_i, h_i - 1, \dots, l_M, h_M)$ to current state x is given by

$$\Psi_c^{i2} = \begin{cases} \lambda_{OA_i}, & \text{if } h_i > 0 \text{ and } \sum_{k=1}^M l_k = B_1, \\ [1 - P(C_1 > C_i)] \cdot \lambda_{OA_i}, & \text{if } h_i > 0 \text{ and } \sum_{k=1}^M l_k < B_1. \end{cases} \quad (3.45)$$

For *Event* (d), when an active mobile user in network N_1 completes its call in area A_i ($2 \leq i \leq M$), the state transits from current state x to state $(l_1, \dots, l_i - 1, h_i, \dots, l_M, h_M)$. The transition rate Λ_d^{i1} is given by

$$\Lambda_d^{i1} = l_i \cdot \mu_c, \text{ if } l_i > 0. \quad (3.46)$$

Similarly, if an active mobile user of network N_i ($2 \leq i \leq M$) completes its communication before it moves out of area A_i , the state transits from current state x to state $(l_1, \dots, l_i, h_i - 1, \dots, l_M, h_M)$. The transition rate Λ_d^{i2} is given by

$$\Lambda_d^{i2} = h_i \cdot \mu_c, \text{ if } h_i > 0. \quad (3.47)$$

There are two state transitions to current state x due to *Event* (d). The transition rate Ψ_d^{i1} from state $(l_1, \dots, l_i + 1, h_i, \dots, l_M, h_M)$ to current state x is given by

$$\Psi_d^{i1} = (l_i + 1) \cdot \mu_c, \text{ if } \sum_{k=1}^M l_k < B_1. \quad (3.48)$$

The state also can transit from state $(l_1, \dots, l_i, h_i + 1, \dots, l_M, h_M)$ to current state x with a transition rate Ψ_d^{i2} , which is given by

$$\Psi_d^{i2} = (h_i + 1) \cdot \mu_c, \text{ if } h_i < B_i. \quad (3.49)$$

For *Event* (e), when an active mobile user moves from area A_s to A_i ($2 \leq i \leq M$), the mobile user makes a vertical handoff to network N_i ($2 \leq i \leq M$) if there are free bandwidth units in network N_i . Otherwise, the mobile user still keeps its connection with network N_1 . The state transition from current state x to state $(l_1 - 1, \dots, l_i + 1, h_i, \dots, l_M, h_M)$ implies no vertical handoff and the transition rate Λ_e^{i1} is given by

$$\Lambda_e^{i1} = l_1 \cdot \mu_{A_{si}}, \text{ if } h_i = B_i \text{ and } l_1 > 0. \quad (3.50)$$

If the mobile user successfully makes a vertical handoff to network N_i , the state transits from current state x to state $(l_1 - 1, \dots, l_i, h_i + 1, \dots, l_M, h_M)$ with the transition rate Λ_e^{i2} that is given by

$$\Lambda_e^{i2} = l_1 \cdot \mu_{A_{si}}, \text{ if } h_i < B_i \text{ and } l_1 > 0. \quad (3.51)$$

There are two state transitions to current state x due to *Event* (e). The state transits from state $(l_1 + 1, \dots, l_i - 1, h_i, \dots, l_M, h_M)$ to current state x if no vertical handoff happens. This transition has the transition rate Ψ_e^{i1} which is given by

$$\Psi_e^{i1} = (l_1 + 1) \cdot \mu_{A_{si}}, \text{ if } l_i > 0 \text{ and } h_i = B_i. \quad (3.52)$$

If a vertical handoff happens when an active mobile user moves from area A_s to A_i , the state transits from state $(l_1 + 1, \dots, l_i, h_i - 1, \dots, l_M, h_M)$ to current state x with the transition rate Ψ_e^{i2} which is given by

$$\Psi_e^{i2} = (l_1 + 1) \cdot \mu_{A_{si}}, \text{ if } h_i > 0. \quad (3.53)$$

For *Event* (f), an active mobile user in area A_i ($2 \leq i \leq M$) may connect to network N_1 or network N_i ($2 \leq i \leq M$). If the mobile user connects to network N_1 , it still keeps its connection to N_1 when it moves out of area A_i . The state transits from current state x to state $(l_1 + 1, \dots, l_i - 1, h_i, \dots, l_M, h_M)$ with the transition rate Λ_f^{i1} which is given by

$$\Lambda_f^{i1} = l_i \cdot \mu_{A_i}, \text{ if } l_i > 0. \quad (3.54)$$

If the active mobile user connects to network N_i ($2 \leq i \leq M$), it has to make a vertical handoff from network N_i to network N_1 when it moves out of area A_i . If there is no free bandwidth unit in network N_1 , the vertical handoff call is forcedly terminated. Therefore, there are two possible state transitions for the arrival of a vertical handoff call, which implies successful vertical handoff and failed one. If the vertical handoff succeeds, the state transits from current state x to state $(l_1 + 1, \dots, l_i, h_i - 1, \dots, l_M, h_M)$. If the vertical handoff fails, the state transits from current state x to state $(l_1, \dots, l_i, h_i - 1, \dots, l_M, h_M)$. Although there are two state transitions, they have the same transition rate Λ_f^{i2} that is given by

$$\Lambda_f^{i2} = h_i \cdot \mu_{A_i}, \text{ if } h_i > 0. \quad (3.55)$$

There are three possible state transitions to current state x due to *Event (f)*. If an active mobile user connects to network N_1 , the state transits from state $(l_1 - 1, \dots, l_i + 1, h_i, \dots, l_M, h_M)$ to current state x when the mobile user moves out of area A_i ($2 \leq i \leq M$). The transition rate Ψ_f^{i1} is given by

$$\Psi_f^{i1} = (l_i + 1) \cdot \mu_{A_i}, \text{ if } l_i > 0. \quad (3.56)$$

If the active mobile user connects to network N_i ($2 \leq i \leq M$), the state transits from state $(l_1 - 1, \dots, l_i, h_i + 1, \dots, l_M, h_M)$ or $(l_1, \dots, l_i, h_i + 1, \dots, l_M, h_M)$ to current state x , which corresponds to successful vertical handoff or failed one. However, both state transitions have the same transition rate Ψ_f^{i2} that is given by

$$\Psi_f^{i2} = (h_i + 1) \cdot \mu_{A_i}, \text{ if } h_i < B_i. \quad (3.57)$$

The equilibrium state probabilities $P(x)$ s ($x \in \chi$) are related to each other by global balanced equations obtained from the state transition diagram. Beside the state balanced equations, the

summation of probabilities of all the states is equal to 1, i.e.,

$$\sum_{x \in \chi} P(x) = 1. \quad (3.58)$$

3.4.4 Performance Analysis

Combining the global balanced equations with Equation (3.58), we can use all the equations to calculate the equilibrium probability of each state. By using successive overrelaxation (SOR) algorithm as shown in Algorithm 1, all the state probabilities can be obtained. In the following, we present the major performance like the blocking probability of originating calls, the forced termination probability of horizontal and vertical handoff calls.

A. Blocking Probability of Originating Calls:

When an originating call is generated in area A_s , it is blocked if there is no free bandwidth unit in the marked cell of network N_1 . That is, the system state has to satisfy $\sum_{i=1}^M l_i = B_1$. We define a state space χ_s that includes all the possible states when a blocking event happens in area A_s , which is given by

$$\chi_s = \left\{ x \mid \sum_{k=1}^M l_k = B_1 \right\}. \quad (3.59)$$

Therefore, the blocking probability of originating calls in area A_s is given by

$$P_{BA_s} = \sum_{x \in \chi_s} P(x). \quad (3.60)$$

When an originating call is generated in area A_i ($2 \leq i \leq M$), it is blocked only if there is no free bandwidth unit in both networks N_1 and N_i ($2 \leq i \leq M$). We define a state space χ_i ($2 \leq i \leq M$), which includes all the possible states when a blocking event happens in area A_i . χ_i is given by

$$\chi_i = \left\{ x \mid \sum_{k=1}^M l_k = B_1 \text{ and } h_i = B_i \right\}, \text{ for } 2 \leq i \leq M. \quad (3.61)$$

Algorithm 1 : Pseudocode of SOR algorithm to calculate equilibrium state probabilities

1. Assign a very small positive value to ϵ to check convergence;
 2. Assign a value between 1 and 2 to w ;
 3. $k = 0$;
 4. Select arbitrary initial (positive) value for λ_{HH}^{k+1} ;
 5. **Repeat**
 6. $k = k + 1$;
 7. Assign arbitrary (positive) values for all probabilities $P(x)$ s;
 8. Normalize all probabilities $P(x)$ s using Equation (3.58);
 9. **Repeat**
 10. **for all states x do**
 11. $P^*(x) = P(x)$;
 12. **end for**
 13. **for all states x do**
 14. Calculate equilibrium state probabilities $\hat{P}(x)$ s using the global balanced equations;
 15. $P(x) = w \cdot \hat{P}(x) + (w - 1) \cdot P(x)$;
 16. **end for**
 17. **Until** $\sum_{x \in \chi} \left| \frac{\hat{P}(x) - P(x)}{\hat{P}(x) + P(x)} \right| < \epsilon$;
 18. Calculate λ_{HH}^{k+1} from obtained state probabilities $P(x)$ s;
 19. **Until** $\left| \frac{\lambda_{HH}^{k+1} - \lambda_{HH}^k}{\lambda_{HH}^{k+1} + \lambda_{HH}^k} \right| < \epsilon$;
-

Consequently, the blocking probability of originating calls in area A_i ($2 \leq i \leq M$) is given by

$$P_{BA_i} = \sum_{x \in \chi_i} P(x), \text{ for } 2 \leq i \leq M. \quad (3.62)$$

Since mobile users are uniformly distributed in the whole cell, the average blocking probability of the whole cell is given by

$$P_B = \frac{\lambda_{OA_s} P_{BA_s} + \sum_{k=2}^M \lambda_{OA_k} P_{BA_k}}{\lambda_O}. \quad (3.63)$$

B. Forced Termination Probability of Horizontal Handoff Calls:

When an active mobile user moves into the marked cell from a neighboring cell in network N_1 , it is terminated if there is no free bandwidth unit in the marked cell of network N_1 . That is, the system state has to satisfy $\sum_{k=1}^M l_k = B_1$. Therefore, the forced termination probability P_{HH} of horizontal handoff calls is given by Equation (3.60). Obviously, the forced termination probability of horizontal handoff calls is equal to the blocking probability of originating calls in area A_s because both types of calls are treated equally.

C. Forced Termination Probability of Vertical Handoff Calls:

When an active mobile user of network N_i ($2 \leq i \leq M$) moves out area A_i ($2 \leq i \leq M$), it has to change its connection from network N_i ($2 \leq i \leq M$) to N_1 . If there is no free bandwidth unit in network N_1 , the vertical handoff call is terminated. Therefore, the forced termination probability P_{VH} of vertical handoff calls is equal to P_{HH} , which is given by Equation (3.60).

D. Average Received Signal Strength of Originating Calls from Network N_i ($2 \leq i \leq M$):

Assume the transmitted signal strength from network N_i ($2 \leq i \leq M$) is equal to 0 dB. In the proposed strategy, an originating call in area A_i ($2 \leq i \leq M$) is accepted by network N_i if

network N_1 does not have any free bandwidth unit. It is also accepted by network N_i if both networks (N_1 and N_i) have free bandwidth units and the cost of network N_i is larger than that of network N_1 . We define a state space χ_i^{F1} ($2 \leq i \leq M$), which includes all the possible states when network N_1 does not have any free bandwidth unit and network N_i has free bandwidth units. χ_i^{F1} is given by

$$\chi_i^{F1} = \left\{ x \mid \sum_{k=1}^M l_k = B_1 \text{ and } h_i < B_i \right\}, \text{ for } 2 \leq i \leq M. \quad (3.64)$$

We define another state space χ_i^{F2} ($2 \leq i \leq M$), which includes all the possible states when both networks (N_1 and N_i) have free bandwidth units. χ_i^{F2} is given by

$$\chi_i^{F2} = \left\{ x \mid \sum_{k=1}^M l_k < B_1 \text{ and } h_i < B_i \right\}, \text{ for } 2 \leq i \leq M. \quad (3.65)$$

Therefore, the number of originating calls accepted by network N_i ($2 \leq i \leq M$) in unit time is given by

$$Y_{N_i} = \lambda_{OA_i} \cdot \left[\sum_{x \in \chi_i^{F1}} P(x) + \sum_{x \in \chi_i^{F2}} P(x)P(C_i > C_1|x) \right]. \quad (3.66)$$

For the originating calls accepted by network N_i ($2 \leq i \leq M$), the average received signal strength from network N_i is related to the bandwidth availability in both networks N_1 and N_i . As a result, we use $P_i^{avg}(x)$ to denote the average received signal strength from network N_i ($2 \leq i \leq M$) when the system is in state x . The sum of the received signal strength from network N_i ($2 \leq i \leq M$) in unit time is given by

$$P_i^{sum} = \lambda_{OA_i} \cdot \left[\sum_{x \in \chi_i^{F1}} P(x)P_i^{avg}(x) + \sum_{x \in \chi_i^{F2}} P(x)P_i^{avg}(x)P(C_i > C_1|x) \right]. \quad (3.67)$$

As a result, the average received signal strength $E[P_i^{avg}(x)]$ from network N_i ($2 \leq i \leq M$) is given by

$$\bar{P}_i = \frac{P_i^{sum}}{Y_{N_i}}, \text{ for } 2 \leq i \leq M. \quad (3.68)$$

3.5 Numerical Results and Discussions

In our analysis model, we consider an IHWMN that has three types of networks N_1 , N_2 , and N_3 . There are only one cell of network N_2 and one cell of network N_3 in each cell of network N_1 . We assume that the radiuses of network N_1 , N_2 , and N_3 are 600 m, 180 m, and 200 m. The total bandwidth units in each network are set to $B_1 = 20$, $B_2 = 5$ and $B_3 = 6$. The average of moving speed is set to $E[V] = 10$ m/s, and w_g is set to 0.2 in CFNS strategy.

We also use extensive simulations to verify our analysis. In the simulations, we assume that network N_1 has 10×10 cells that fill the entire service area. In our simulation model, when a mobile user in the edge cell moves out of the service area, we assume that the same mobile user moves into the other side of the service area through a horizontal handoff between two corresponding cells. For example, when a mobile user moves out of the service area from left side, it moves into the service area from right side immediately. By doing this, we can simulate a very large coverage of WMNs using limited number of cells.

First of all, we examine the blocking probabilities of originating calls in different areas of the marked cell. Figures. 3.3, 3.4, and 3.5 show the blocking probabilities of originating calls in different areas in TBNS, RSNS, and CFNS strategies, respectively. The offered traffic load is defined as λ_O/μ_c . We can observe that the blocking probability of originating calls in area A_2 (or A_3) in RSNS strategy is slightly lower than that in CFNS strategy. However, this benefit sacrifices the blocking probability in area A_s . Without considering the traffic load, bandwidth units in network N_1 are probable to be allocated to the originating calls that are generated in area A_2 or A_3 . The originating calls that are generated in area A_s have less chance to obtain the bandwidth unit from network N_1 . As a result, the blocking probability of originating calls of area A_s in RSNS strategy is the highest. The simulation results also verify our analysis.

Figure 3.3: Blocking probability of originating calls in area A_s

We then examine the blocking probability of originating calls of the whole cell. As shown in Figure 3.6, the blocking probabilities of originating calls in TBNS, RSNS, and CFNS strategies have a small difference. The RSNS strategy achieves the worst system performance because it does not consider the traffic load between different types of networks, while received signal strength is the only decision factor.

In RSNS strategy, the originating calls in area A_2 is accepted by network N_1 if both networks N_1 and N_2 have free bandwidth units and the cost of network N_1 is larger than that of network N_2 . The originating call that has a stronger received signal strength from network N_2 has a larger cost of network N_2 , which has a higher probability to be accepted by network N_2 . Therefore, the average received signal strength of the originating calls accepted by network N_2 becomes larger in RSNS strategy. In this thesis, we compare the average received signal strength given

Figure 3.4: Blocking probability of originating calls in area A_2

the transmitted signal strength is equal to 0 dB. Figure 3.7 shows the average signal strength in TBNS, RSNS, and CFNS strategies, respectively. As a special case of CFNS strategy, RSNS strategy ($w_g = 0$) achieves the strongest average received signal strength. On the other hand, as another special case of CFNS strategy, TBNS strategy ($w_g = 1$) achieves the worst received signal strength because TBNS strategy does not consider the received signal strength. When the offered traffic load increases, the probability that networks N_1 has free bandwidth units decreases. As a result, the call has to be accepted by a network which has free bandwidth units without considering the cost function. Therefore, the average received signal strength becomes worse when the offered traffic load increases as shown in Figure 3.7.

Figures 3.8 and 3.9 show the blocking probability of originating calls and average received signal strength in CFNS strategy with different weights w_g . We can observe that, with the

Figure 3.5: Blocking probability of originating calls in area A_3

decreasing w_g , the blocking probability becomes worse while the average received signal strength becomes better. It is obvious that the CFNS strategy with different weights can achieve the tradeoff between the blocking probability of of originating calls in the whole cell and the average received signal strength.

3.6 Summary

In this chapter, we proposed a system model for an IHWMN. We also proposed a cost-function-based network selection strategy to combine the traffic balance and received signal strength among different types of WMNs. The system performance is analyzed by using theoretical model and simulations. The results have shown that the proposed CFNS strategy can achieve a tradeoff between the blocking probability of originating calls and the average received

Figure 3.6: Blocking probability of originating calls in the whole cell

signal strength, which are very important for both systems and users.

Figure 3.7: Average received signal strength (in dB) from network N_2

Figure 3.8: Blocking probability of originating calls with different weights

Figure 3.9: Average received signal strength (in dB) from network N_2 with different weights

Chapter 4

Preemption-based Resource Management Scheme

4.1 Introduction

Resource management scheme to support multiple traffic in IHWMNs has to consider the heterogeneities of traffic and networks. Although there are a lot of resource management schemes have been proposed, they only support multiple traffic in a single type of WMN, or support a single type of traffic in IHWMNs. Therefore, they may not efficiently support multiple traffic in IHWMNs.

In this chapter, we propose and analyze the resource management schemes to support real-time (voice) traffic and non-real-time traffic (data) in IHWMNs. In the next section, we introduce the system model. A resource management scheme to support voice and data traffic in an IHWMN is described in Section 4.3. The system performances of the proposed scheme are

analyzed using theoretical model in Section 4.4. In Section 4.5, an optimization method is presented to achieve the fairness between different types of traffic. Section 4.6 provides the performance evaluation of the proposed scheme. Finally, we conclude this chapter in Section 4.7.

4.2 System Model

We consider an IHWMN having M different types of WMNs. We assume that the entire service area of the system is covered by network N_1 . Network N_1 consists of many homogeneous cells with lower bandwidth service. We also assume that network N_i ($2 \leq i \leq M$) provides a higher bandwidth service than network N_1 with limited coverage. That is, network N_i ($2 \leq i \leq M$) only covers some portions of entire service area and is randomly distributed in the service area. This model is the same as the model in Chapter 3. Similar to Chapter 3, we only focus one cell of network N_1 , which is called marked cell.

We assume that each cell of network N_i ($1 \leq i \leq M$) has a circular cell shape with radius R_i . The area covered by network N_i ($2 \leq i \leq M$) is defined as area A_i . The area that is only covered by network N_1 is defined as area A_1 , which is defined as A_s in Chapter 3. Each cell of network N_i ($1 \leq i \leq M$) is assumed to have total B_i logic channels. Note that the bandwidth of one logic channel in a higher bandwidth network N_i ($2 \leq i \leq M$) is much larger than one basic bandwidth in N_1 . We define that the bandwidth of one logic channel in N_i ($2 \leq i \leq M$) is equal to the bandwidth of β_i logic channels in network N_1 , where $\beta_i > 1$.

We consider that mobile users are uniformly distributed in the service area and they move in all the directions with equal probability. The moving speed V (random variable) follows an arbitrary distribution with a mean value of $E[V]$.

Although there are many types of real-time traffic such as voice and video, we only consider voice traffic as real-time traffic in this thesis for the purpose of simplicity. Similarly, only data traffic is considered here as a non-real-time traffic. In the next section, we introduce a resource management scheme to support both voice and data traffic in an IHWMN.

4.3 Resource Management Scheme to Support Voice and Data Traffic

4.3.1 Handling of Voice Traffic

An ongoing voice call is forcedly terminated due to a failure handoff since voice traffic is delay-sensitive. Therefore, a resource management scheme needs to reduce the number of handoff. On the other hand, a voice call only needs a low bandwidth. The call holding time of a voice call does not change even if a higher bandwidth channel is allocated. In other words, the resource utilization is not efficient if a higher bandwidth channel is allocated to a voice call. Therefore, we assume that a voice call is accepted only by network N_1 to prevent vertical handoff and occupation of a higher bandwidth channel. As a result, there are only two types of voice calls arrival in our system, i.e., originating voice calls and horizontal handoff voice calls. A horizontal handoff voice request is generated in the marked cell when an active voice call user moves into the marked cell from neighboring cells of network N_1 ,

When an originating voice request or horizontal handoff voice request is generated in the marked cell of network N_1 , it is accepted if there are free channels in the marked cell of network N_1 . We assume that voice traffic has a higher priority than data traffic since voice traffic is delay-sensitive. Therefore, an incoming voice call, either originating or horizontal handoff voice

call, can preempt ongoing data call in the marked cell of network N_1 if there is no free channel upon its arrival. We adopt a queue to hold those preempted data calls in the marked cell of network N_1 . Two concerns may arise in such preemption-based resource management scheme. First of all, excessive preemption easily results in unfairness between voice traffic and data traffic, which must be avoided. The other concern is the priority of horizontal handoff voice calls over originating voice calls. From a user's point of view, terminating a horizontal handoff voice call is more frustrating than blocking an originating voice call. Therefore, higher priority should be provided to horizontal handoff voice calls. In some channel reservation schemes [19] [20], certain logic channels are exclusively reserved for handoff calls to provide such priority. However, the originating and horizontal handoff voice calls completely share the resources in our scheme unlike the reservation scheme. Therefore, we have to treat them differently during the preemptions in order to provide higher priority to horizontal handoff voice calls. In the next section, we describe how the preemption works to differentiate the originating and horizontal handoff voice calls.

4.3.2 Preemption Policy

Firstly, we do not want to terminate an ongoing data call for accepting an incoming voice call. Therefore, the preemption fails if the queue of the marked cell of network N_1 is full. We further propose two thresholds, V_H^{max} and V_O^{max} , to prevent excessive preemption. Both thresholds are defined as the maximum capacities of ongoing voice calls when an incoming voice call tries to make a preemption. V_H^{max} is used for the preemption of horizontal handoff voice calls, and V_O^{max} is used for the preemption of originating voice calls. In the following, we introduce how the preemption works with V_H^{max} and V_O^{max} .

V_H^{max} is a real value and can be presented as

$$V_H^{max} = \lfloor V_H^{max} \rfloor + \alpha_H, \quad (4.1)$$

where $\lfloor V_H^{max} \rfloor$ is the integral part of V_H^{max} , and α_H is the decimal part of V_H^{max} . Therefore, α_H is given by

$$\alpha_H = V_H^{max} - \lfloor V_H^{max} \rfloor. \quad (4.2)$$

When an incoming horizontal handoff voice call tries to make a preemption, the result of the preemption depends on the value of V_H^{max} and the state of the marked cell, which is given by

- If the number of current ongoing voice calls is less than $\lfloor V_H^{max} \rfloor$, the incoming horizontal handoff call can successfully preempt ongoing data calls if there are ongoing data calls and the queue is not full;
- If the number of current ongoing voice calls is equal to $\lfloor V_H^{max} \rfloor$, the incoming horizontal handoff call can successfully preempt ongoing data calls only with probability α_H if there are ongoing data calls and the queue is not full. In other words, the preemption fails with probability $1 - \alpha_H$;
- If the number of current ongoing voice calls is larger than $\lfloor V_H^{max} \rfloor$, the preemption fails even if there are ongoing data calls and the queue is not full in the marked cell of network N_1 .

When implementing the above preemption scheme, the preemption succeeds (or fails) if the number of current ongoing voice calls is less (or larger) than $\lfloor V_H^{max} \rfloor$. If the number of current ongoing voice calls is equal to $\lfloor V_H^{max} \rfloor$, a random number is generated uniformly in the range of $[0, 1)$. If the generated random number is less than α_H , the preemption succeeds. Otherwise, the preemption fails and the incoming horizontal handoff voice call is forcedly terminated.

Similar to Equation (4.1), V_O^{max} can be presented as

$$V_O^{max} = \lfloor V_O^{max} \rfloor + \alpha_O, \quad (4.3)$$

where $\lfloor V_O^{max} \rfloor$ is the integral part of V_O^{max} , and α_O is the decimal part of V_O^{max} . The preemption of originating voice calls is the same as the preemption of horizontal handoff voice calls except using V_O^{max} instead of V_H^{max} . If the preemption fails, the incoming originating voice call is blocked.

It is obvious that thresholds, V_O^{max} and V_H^{max} , provide certain limitation to the preemption. Since they indicate the upper limit of the current ongoing voice calls in the marked cell when making a preemption, they are in the range of $[0, B_1]$. Since higher priority should be provided to horizontal handoff voice calls as we mentioned in Section 4.3.1, V_H^{max} should be larger than V_O^{max} . Therefore, the constraint of V_O^{max} and V_H^{max} are given by

$$0 \leq V_O^{max} < V_H^{max} \leq B_1. \quad (4.4)$$

It is to note that the limitations imposed by V_H^{max} and V_O^{max} have the discrete features if V_H^{max} and V_O^{max} only take integral values. In order to have continuous limitations on the preemption, we allow V_H^{max} and V_O^{max} to take any real values that satisfy Equation (4.4).

4.3.3 Handling of Data Traffic

Unlike voice traffic, data traffic is delay-tolerant and benefits from a higher bandwidth channel. That is, a higher bandwidth channel can improve the throughput of a data call and reduce its holding time. Therefore, we assume that an originating data call always tries the highest bandwidth network first if there are more than one networks available. When an originating data call is generated in area A_i ($2 \leq i \leq M$), it tries network N_i first. If there is no free channel

in network N_i , the originating data call is put into the queue of network N_i ($2 \leq i \leq M$). When an originating data call is generated in area A_1 , it is accepted by network N_1 if there are free channels in the marked cell of network N_1 . Otherwise, it is put into the queue of network N_1 if the queue is not full or terminated if the queue is full.

If an active data call mobile user moves into the marked cell from neighboring cells of network N_1 , a horizontal handoff data request is generated if only network N_1 is available. The horizontal handoff data call is accepted if there are free channels in the marked cell of network N_1 . Otherwise, it is put into the queue of the marked cell if the queue is not full or terminated if the queue is full. For a data call waiting in the queue of neighboring cells of network N_1 , it also generates a horizontal handoff data request in the marked cell of network N_1 when its mobile user moves into the marked cell.

If an active data call mobile user in area A_1 moves into area A_i ($2 \leq i \leq M$), a DVH (downward vertical handoff) request is generated in the higher bandwidth network N_i . A data call in the queue of network N_1 also generates a DVH request in network N_i ($2 \leq i \leq M$) when its mobile user moves into area A_i . If an active data call mobile user in a higher bandwidth network N_i ($2 \leq i \leq M$) moves out of area A_i before call completion, it generates a UVH (upward vertical handoff) request in an available network N_j ($i \neq j$). A data call in the queue of network N_i ($2 \leq i \leq M$) also generates a UVH request in an available network N_j ($i \neq j$) when the mobile user moves out of area A_i .

The handling of voice and data traffic in the marked cell is shown in Figure 4.1, where the variable notation can be found in Table 4.1.

λ_{OV}	Average arrival rate of originating voice calls
λ_{HHV}	Average arrival rate of horizontal handoff voice calls
λ_{ODA_i} ($1 \leq i \leq M$)	Average arrival rate of originating data calls in area A_i
λ_{HHD}	Average arrival rate of horizontal handoff data calls
λ_{UVH}	Average arrival rate of UVH data calls
λ_{DVH}	Average arrival rate of DVH data calls
λ_{DVH_i} ($2 \leq i \leq M$)	Average arrival rate of DVH data calls from network N_1 to N_i
λ_{UVH_i} ($2 \leq i \leq M$)	Average arrival rate of UVH data calls from network N_i to N_1

Table 4.1: The variable notation

Figure 4.1: System model of the marked cell

4.4 Analysis

In this section, we analyze the system performances of the proposed resource management scheme using theoretical model. In order to simplify the analysis, we assume that each higher bandwidth network only has one cell in the marked cell. Furthermore, the cells of different types of higher bandwidth networks do not overlap with each other and do not cross the cell boundary of the marked cell.

4.4.1 Traffic Model

Because mobile users are uniformly distributed in the marked cell, the average arrival rate of originating data calls in area A_i ($1 \leq i \leq M$) is given by

$$\lambda_{ODA_i} = \frac{A_{A_i}}{\sum_{k=1}^M A_{A_k}} \cdot \lambda_{OD}, \text{ for } 1 \leq i \leq M, \quad (4.5)$$

where A_{A_i} is the area of area A_i .

Using fluid flow model, the outgoing rate $\mu_{A_{1o}}$ of area A_1 to neighboring cells of network N_1 is given by

$$\mu_{A_{1o}} = \frac{E[V]L_{A_{1o}}}{\pi A_{A_1}}, \quad (4.6)$$

where $L_{A_{1o}}$ is the length of the boundary between area A_1 and neighboring cells. Since the cell shape of networks N_i ($1 \leq i \leq M$) is assumed to be circular with radius R_i , $L_{A_{1o}}$ is equal to $2\pi R_1$, and A_{A_1} is given by

$$\begin{aligned} A_{A_1} &= \pi R_1^2 - \sum_{k=2}^M A_{A_k} \\ &= \pi R_1^2 - \pi \sum_{k=2}^M R_k^2. \end{aligned} \quad (4.7)$$

Hence, the outgoing rate $\mu_{A_{1i}}$ ($2 \leq i \leq M$) of area A_1 to area A_i ($2 \leq i \leq M$) in the marked cell is given by

$$\mu_{A_{1i}} = \frac{E[V]L_{A_{1i}}}{\pi A_{A_1}}, \quad (4.8)$$

where $L_{A_{1i}}$ is the length of perimeter of A_i ($2 \leq i \leq M$) and is equal to $2\pi R_i$. Similarly, the cell outgoing rate μ_{cell} of the marked cell is given by

$$\mu_{cell} = \frac{E[V]L_{A_{1o}}}{\pi \sum_{k=1}^M A_{A_k}}. \quad (4.9)$$

The outgoing rate μ_{A_i} of area A_i ($2 \leq i \leq M$) is given by

$$\mu_{A_i} = \frac{E[V]L_{A_{1i}}}{\pi A_{A_i}}. \quad (4.10)$$

We assume that the dwell time T_{cell} (random variable) of voice call mobile users in the marked cell follows exponential distribution with a mean value of $1/\mu_{cell}$. Similarly, the dwell time $T_{A_{1o}}$ (random variable) of data call mobile users in area A_1 before moving out of the marked cell is assumed to follow exponential distribution with a mean value of $1/\mu_{A_{1o}}$. The dwell time $T_{A_{1i}}$ ($2 \leq i \leq M$) (random variable) of data call mobile users in area A_1 before moving into area A_i ($2 \leq i \leq M$) is assumed to follow exponential distribution with a mean value of $1/\mu_{A_{1i}}$. We also assume that the dwell time T_{A_i} ($2 \leq i \leq M$) (random variable) of data call mobile users in area A_i follows exponential distribution with a mean value of $1/\mu_{A_i}$.

The call holding time T_{cV} (random variable) of voice calls is assumed to follow exponential distribution with a mean value of $1/\mu_{cV}$. The call holding time T_{cD} (random variable) of data calls is also assumed to follow exponential distribution with a mean value of $1/\mu_{cD}$ if it is serviced by a logic channel in network N_1 . If a data call is serviced by a higher bandwidth channel in network N_i ($2 \leq i \leq M$), the data call completes sooner since a higher bandwidth channel can significantly increase the throughput of the data call.

4.4.2 Markov Method

Since the arrival processes, either originating or handoff calls, are assumed to be Poisson processes, we can use a three-dimensional Markov chain to model the marked cell of network N_1 . The state of the marked cell of network N_1 can be defined by a three-tuple of nonnegative integers (v_1, d_1, q_1) . v_1 is the number of ongoing voice calls, d_1 is the number of ongoing data calls, and q_1 is the number of data calls in the queue of network N_1 . Apparently, there are $v_1 + d_1$ ongoing calls in the marked cell. For brevity, we use X denote the state space that includes all

the valid states. X is given by

$$X = \{(v_1, d_1, q_1) | [(v_1 + d_1 < B_1) \cap (q_1 = 0)] \cup [(v_1 + d_1 = B_1) \cap (q_1 \leq Q_1)]\}, \quad (4.11)$$

where Q_1 is the queue size of the marked cell of network N_1 .

The state transitions are driven by events such as call arrival and call completion. Figure 4.2 shows the state transition from the current state (v_1, d_1, q_1) . The state may transit along the dotted line or solid line, which depends the current state. It is to note that not every event results in deterministic state transition. For example, there is no state transition if an originating voice call is blocked. In the following, we analyze the state transitions events by events.

Figure 4.2: Semi transaction diagram of the current state (v_1, d_1, q_1)

Event (a) - *Arrival of originating or horizontal handoff voice calls*: When an originating or horizontal handoff voice call is generated, it is accepted network N_1 if there are free channels in the marked cell of network N_1 . Hence, the state transits from current state (v_1, d_1, q_1) to state $(v_1 + 1, d_1, q_1)$ with the transition rate $\lambda_{OV} + \lambda_{HHV}$. If there is no free channel in the marked cell, the incoming voice call tries to preempt ongoing data calls in the marked cell of network N_1 . We define two state spaces, X_{O1} and X_{O2} , to include the states that the preemption of an

originating voice call may succeed. X_{O1} is given by

$$X_{O1} = \{(v_1, d_1, q_1) | (v_1 + d_1 = B_1) \cap (v_1 < \lfloor V_O^{max} \rfloor) \cap (d_1 > 0) \cap (q_1 < Q_1)\}, \quad (4.12)$$

which includes all the states that the preemption of an originating voice call definitely succeeds.

X_{O2} is given by

$$X_{O2} = \{(v_1, d_1, q_1) | (v_1 + d_1 = B_1) \cap (v_1 = \lfloor V_O^{max} \rfloor) \cap (d_1 > 0) \cap (q_1 < Q_1)\}, \quad (4.13)$$

which includes all the valid states that the preemption of an originating voice call succeeds with probability α_O . In other words, the preemption fails with probability $1 - \alpha_O$. As a result, the transition rate Λ_{OV} due to originating call arrivals is given by

$$\Lambda_{OV} = \begin{cases} \lambda_{OV}, & \text{if } v_1 + d_1 < B_1, \\ \lambda_{OV}, & \text{if } (v_1, d_1, q_1) \in X_{O1}, \\ \alpha_O \lambda_{OV}, & \text{if } (v_1, d_1, q_1) \in X_{O2}. \end{cases} \quad (4.14)$$

Similarly, we define two state spaces X_{H1} and X_{H2} to include all the valid states that the preemption of a horizontal handoff voice call may succeed. X_{H1} is given by

$$X_{H1} = \{(v_1, d_1, q_1) | (v_1 + d_1 = B_1) \cap (v_1 < \lfloor V_H^{max} \rfloor) \cap (d_1 > 0) \cap (q_1 < Q_1)\}, \quad (4.15)$$

which includes all the valid states that the preemption of a horizontal handoff voice call definitely succeeds. X_{H2} is given by

$$X_{H2} = \{(v_1, d_1, q_1) | (v_1 + d_1 = B_1) \cap (v_1 = \lfloor V_H^{max} \rfloor) \cap (d_1 > 0) \cap (q_1 < Q_1)\}, \quad (4.16)$$

which includes all the valid states that the preemption of a horizontal handoff voice call succeeds with probability α_H . As a result, the transition rate Λ_{HHV} due to horizontal handoff voice call

arrivals is given by

$$\Lambda_{HHV} = \begin{cases} \lambda_{HHV}, & \text{if } v_1 + d_1 < B_1, \\ \lambda_{HHV}, & \text{if } (v_1, d_1, q_1) \in X_{H1}, \\ \alpha_H \lambda_{HHV}, & \text{if } (v_1, d_1, q_1) \in X_{H2}. \end{cases} \quad (4.17)$$

Event (b) - Data call arrival: There are three types of data calls that arrive to the marked cell of network N_1 , i.e., originating data calls in area A_1 , horizontal handoff data calls from neighboring cells, and UVH (upward vertical handoff) data calls from network N_i ($2 \leq i \leq M$). We do not treat these data calls differently. The incoming data call is accepted if there are free channels in the marked cell, and the state transits from current state (v_1, d_1, q_1) to state $(v_1, d_1 + 1, q_1)$. Otherwise, the incoming data call is put into the queue of network N_1 if the queue is not full and the state transits from current state (v_1, d_1, q_1) to state $(v_1, d_1, q_1 + 1)$. As a result, the transition rate Λ_D due to data call arrivals in the marked cell of network N_1 is given by

$$\Lambda_D = \lambda_{ODA_1} + \lambda_{HHD} + \lambda_{UVH}, \text{ if } q_1 < Q_1. \quad (4.18)$$

Event (c) - Voice calls completion or moving out of the marked cell: If an active voice call mobile user completes the call in the marked cell, or moves out of the marked cell before call completion, the occupied channel is released. The released channel can be reallocated to the data calls waiting in the queue. If there is no data call in the queue, the state transits from current state (v_1, d_1, q_1) to state $(v_1 - 1, d_1, q_1)$. If there are data calls in the queue, the state transits from current state (v_1, d_1, q_1) to state $(v_1 - 1, d_1 + 1, q_1 - 1)$. The transition rate Λ_{VC} due to event c) is given by

$$\Lambda_{VC} = v_1 \cdot (\mu_{cell} + \mu_{cV}), \text{ if } v_1 > 0. \quad (4.19)$$

Event (d) - *Data call completion or moving out of area A_1* : If an active data call mobile user completes the call in area A_1 , the occupied channel is released. The released channel can be reallocated to the data calls waiting in the queue. As a result, the state transits from current state (v_1, d_1, q_1) to state $(v_1, d_1 - 1, q_1)$ if there is no data call in the queue. If there are data calls in the queue, the state transits from current state (v_1, d_1, q_1) to state $(v_1, d_1, q_1 - 1)$. The same state transition happens when an active data call mobile user moves out of the marked cell of network N_1 , or moves from area A_1 into other areas A_i ($2 \leq i \leq M$) covered by higher bandwidth network N_i . Therefore, the transition rate Λ_{DC} due to *event d*) is given by

$$\Lambda_{DC} = d_1 \cdot (\mu_{cD} + \mu_{A_{1o}} + \sum_{k=2}^M \mu_{A_{1k}}), \text{ if } d_1 > 0. \quad (4.20)$$

Event (e) - *Data call in the queue moving out of area A_1* : If a mobile user holding a data call in the queue moves out of the marked cell of network N_1 , or moves into other area A_i ($2 \leq i \leq M$) before it obtains a channel, the state transits from current state (v_1, d_1, q_1) to state $(v_1, d_1, q_1 - 1)$. The transition rate Λ_Q due to *event e*) is given by

$$\Lambda_Q = q_1 \cdot (\mu_{A_{1o}} + \sum_{k=2}^M \mu_{A_{1k}}), \text{ if } q_1 > 0. \quad (4.21)$$

The equilibrium state probabilities $P(v_1, d_1, q_1)$ s are related to each other by global balanced equations obtained from the above state transitions. Beside the state balanced equations, the summation of all the state probabilities is equal to 1, which is given by

$$\sum_{(v_1, d_1, q_1) \in X} P(v_1, d_1, q_1) = 1. \quad (4.22)$$

Combining global balanced equations with Equation (4.22), we can calculate the equilibrium probability of each state by using SOR algorithm. Then, the DVH rate λ_{DVH_i} from network N_1 to N_i ($2 \leq i \leq M$) can be obtained as

$$\lambda_{DVH_i} = \mu_{A_{1i}} \sum_{(v_1, d_1, q_1) \in X} (d_1 + q_1) \cdot P(v_1, d_1, q_1). \quad (4.23)$$

Similarly, the arrival rate λ_{HHV} of horizontal handoff voice calls is given by

$$\lambda_{HHV} = \mu_{cell} \sum_{(v_1, d_1, q_1) \in X} v_1 \cdot P(v_1, d_1, q_1), \quad (4.24)$$

and the arrival rate λ_{HHD} of horizontal handoff data calls is given by

$$\lambda_{HHD} = \mu_{A_{1o}} \sum_{(v_1, d_1, q_1) \in X} (d_1 + q_1) \cdot P(v_1, d_1, q_1). \quad (4.25)$$

Since only data calls are accepted by network N_i ($2 \leq i \leq M$), network N_i can be modeled as a $M/M/B_i/B_i + Q_i$ queue that has B_i servers and Q_i waiting rooms. The average call arrival rate is $\lambda_{ODA_i} + \lambda_{DVH_i}$ which correspond to the originating data calls in area A_i ($2 \leq i \leq M$) and DVH calls from network N_1 . Note that the completion rate of ongoing data calls in network N_i ($2 \leq i \leq M$) is $\beta_i \mu_{cD}$ since the bandwidth of a logic channel in network N_i ($2 \leq i \leq M$) is equal to the bandwidth of β_i logic channels in network N_1 . The equilibrium state probability $P(l_i)$ of network N_i ($2 \leq i \leq M$) can be easily obtained from $M/M/S_i/S_i + Q_i$ queue [53]. Then, the UVH rate λ_{UVH_i} from network N_i ($2 \leq i \leq M$) to N_1 is obtained from

$$\lambda_{UVH_i} = \mu_{A_i} \sum_{1 \leq l_i \leq S_i + Q_i} P(l_i), \text{ for } 2 \leq i \leq M. \quad (4.26)$$

Therefore, the total UVH rate λ_{UVH} to network N_1 is given by

$$\lambda_{UVH} = \sum_{i=2}^M \lambda_{UVH_i}. \quad (4.27)$$

4.4.3 Performance Analysis

Since λ_{HHV} , λ_{HHD} , λ_{DVH_i} , and λ_{UVH} are unknown in the beginning, we design an iterative algorithm to calculate all the equilibrium state probabilities, $P(v_1, d_1, q_1)$ s and $P(l_i)$ s, as shown in Algorithm 2.

Algorithm 2 : Pseudocode of iterative algorithm

1. Assign a very small positive value to ϵ to check convergence;
 2. $k = 0$;
 3. Select arbitrary initial (positive) value for λ_{UVH}^{k+1} ;
 4. **Repeat**
 5. $k = k + 1$;
 6. $j = 0$;
 7. Select arbitrary initial (positive) values for λ_{HHD}^{j+1} and λ_{HHV}^{j+1} ;
 8. **Repeat**
 9. $j = j + 1$;
 10. Calculate the equilibrium state probabilities $P(v_1, d_1, q_1)$ s using λ_{HHD}^j and λ_{HHV}^j ;
 11. Calculate the λ_{HHD}^{j+1} and λ_{HHV}^{j+1} using $P(v_1, d_1, q_1)$ s;
 12. **Until** $\left| \frac{\lambda_{HHD}^{j+1} - \lambda_{HHD}^j}{\lambda_{HHD}^{j+1} + \lambda_{HHD}^j} \right| < \epsilon$ **and** $\left| \frac{\lambda_{HHV}^{j+1} - \lambda_{HHV}^j}{\lambda_{HHV}^{j+1} + \lambda_{HHV}^j} \right| < \epsilon$;
 13. Calculate λ_{DVH_i} from $P(v_1, d_1, q_1)$ s for $2 \leq i \leq M$;
 14. Calculate equilibrium state state probabilities $P(l_i)$ of network N_i ($2 \leq i \leq M$);
 15. Calculate λ_{UVH}^{k+1} ;
 16. **Until** $\left| \frac{\lambda_{UVH}^{k+1} - \lambda_{UVH}^k}{\lambda_{UVH}^{k+1} + \lambda_{UVH}^k} \right| < \epsilon$;
-

The major system performances can be presented using the obtained equilibrium state probabilities $P(v_1, d_1, q_1)$ s and $P(l_i)$ s. For example, the blocking probability B_{OV} of originating voice calls is given by

$$B_{OV} = \sum_{(v_1, d_1, q_1) \in X_{O2}} (1 - \alpha_O) \cdot P(v_1, d_1, q_1) + \sum_{(v_1, d_1, q_1) \in X_{O3}} P(v_1, d_1, q_1), \quad (4.28)$$

where the state space X_{O2} is given by Equation (4.13) and X_{O3} is given by

$$X_{O3} = \{(v_1, d_1, q_1) | (v_1 + d_1 = B_1) \cap [(v_1 > \lfloor V_O^{max} \rfloor) \cup (d_1 = 0) \cup (q_1 = Q_1)]\}. \quad (4.29)$$

The state space X_{O3} includes all the valid states that the preemption of an originating voice call definitely fails.

Similarly, the forced termination probability of horizontal handoff voice calls is given by

$$B_{HHV} = \sum_{(v_1, d_1, q_1) \in X_{H2}} (1 - \alpha_H) \cdot P(v_1, d_1, q_1) + \sum_{(v_1, d_1, q_1) \in X_{H3}} P(v_1, d_1, q_1), \quad (4.30)$$

where the state spaces X_{H2} is given by Equation (4.16) and X_{H3} is given by

$$X_{H3} = \{(v_1, d_1, q_1) | (v_1 + d_1 = B_1) \cap [(v_1 > \lfloor V_H^{max} \rfloor) \cup (d_1 = 0) \cup (q_1 = Q_1)]\}. \quad (4.31)$$

Like X_{O3} , the state space X_{H3} includes all the valid states that the preemption of a horizontal handoff call definitely fails.

An originating data call is blocked in area A_1 if there is no free channel in the marked cell of network N_1 and the queue is full. Therefore, the blocking probability B_{ODA_1} of originating data calls in area A_1 is given by

$$B_{ODA_1} = \sum_{(v_1, d_1, q_1) \in X_{ODA_1}} P(v_1, d_1, q_1), \quad (4.32)$$

where the state space X_{ODA_1} is given by

$$X_{ODA_1} = \{(v_1, d_1, q_1) | [(v_1, d_1, q_1) \in X] \cap [q_1 = Q_1]\}. \quad (4.33)$$

It is obvious that X_{ODA_1} consists of all the valid states that an incoming data call in area A_1 is blocked.

The average number of data calls $E[q_1]$ in the queue of network N_1 is given by

$$E[q_1] = \sum_{(v_1, d_1, q_1) \in X} q_1 \cdot P(v_1, d_1, q_1). \quad (4.34)$$

According to Little's law [53], the average delay $E[t]$ of data calls in area A_1 is given by

$$E[t] = \frac{E[q_1]}{(\lambda_{ODA_1} + \lambda_{HHD} + \lambda_{UVH}) \cdot (1 - B_{ODA_1})}. \quad (4.35)$$

4.5 Fairness Issue

The aim of WMNs is to provide desired services to mobile users, which can be measured using QoS requirements. Two main QoS requirements of voice traffic are the blocking probability B_{OV} of originating calls and the forced termination probability B_{HHV} of handoff calls. For data traffic, main QoS requirements include the blocking probability of originating data calls and the average delay. In our system, the QoS requirements of voice traffic are our main concern. We also do not want to ignore the performances of data traffic. That is, the system provides the guaranteed B_{OV} and B_{HHV} to voice traffic and the best effort service to data traffic. In other words, B_{OV} and B_{HHV} must be less than certain thresholds. Therefore, we define two probability thresholds, B_{OV}^{th} and B_{HHV}^{th} , where the blocking probability of originating voice calls must not be larger than B_{OV}^{th} and the forced termination probability of handoff voice calls must not be larger than B_{HHV}^{th} .

Intuitively, by increasing the values of V_O^{max} and V_H^{max} , B_{OV} and B_{HHV} decrease since the originating voice calls and the horizontal handoff voice calls obtain more priority. Since resources are completely shared by voice and data traffic, the performances of data traffic deteriorate

Algorithm 3 : Pseudocode of optimization algorithm (version 1)

Step 1. Assign a very small positive value to ϵ to check convergence;

Step 2. Set initial value: $V_O^{high} = B_1$, $V_O^{low} = 0$, $V_O^{max} = 0.5(V_O^{high} + V_O^{low})$;

Step 3. $V_H^{high} = B_1$, $V_H^{low} = V_O^{max}$, $V_H^{max} = 0.5(V_H^{high} + V_H^{low})$;

Step 4. Use Algorithm 2 to calculate the blocking probability B_{OV} of originating voice calls

and the forced termination probability B_{HHV} of handoff voice calls;

Step 5. If $|\frac{B_{HHV} - B_{HHV}^{th}}{B_{HHV} + B_{HHV}^{th}}| > \epsilon$, go to step 6; otherwise go to Step 9;

Step 6. If $B_{HHV} > B_{HHV}^{th}$, go to Step 7; otherwise, go to Step 8;

Step 7. $V_H^{low} = V_H^{max}$, $V_H^{max} = 0.5(V_H^{low} + V_H^{high})$, if $B_1 - V_H^{max} < \epsilon$, go to Step 14; otherwise,
go to Step 4;

Step 8. $V_H^{high} = V_H^{max}$, $V_H^{max} = 0.5(V_H^{low} + V_H^{high})$, if $V_H^{max} - V_O^{max} < \epsilon$, go to Step 12; otherwise,
go to Step 4;

Step 9. If $|\frac{B_{OV} - B_{OV}^{th}}{B_{OV} + B_{OV}^{th}}| > \epsilon$, go to Step 10; otherwise, go to Step 13;

Step 10. If $B_{OV} > B_{OV}^{th}$, go to Step 11; otherwise, go to Step 12;

Step 11. $V_O^{low} = V_O^{max}$, $V_O^{max} = 0.5(V_O^{low} + V_O^{high})$, go to Step 3;

Step 12. $V_O^{high} = V_O^{max}$, $V_O^{max} = 0.5(V_O^{low} + V_O^{high})$, go to Step 3;

Step 13. End and return V_H^{max} and V_O^{max} ;

Step 14. End without proper V_H^{max} and V_O^{max} .

simultaneously when the performances of voice traffic improve. If the QoS requirements of voice traffic have been met, the further increase of V_O^{max} and V_H^{max} imposes the unfairness to data traffic. In order to provide the best effort service to data traffic and guaranteed QoS to voice traffic, we have to find the minimum values of V_O^{max} and V_H^{max} that satisfy the QoS requirements of voice traffic. It is obvious that these minimum values of V_O^{max} and V_H^{max} result in the best performances for data traffic.

The bisection algorithm [54] can be used to search the minimum values of V_H^{max} and V_O^{max} subject to the QoS requirements of voice traffic. The search algorithm is shown as Algorithm 3 and is divided into two loops. The inner loop is to find the minimum V_H^{max} and the outer loop is to find the minimum V_O^{max} . The algorithm also ensures that V_H^{max} is larger than V_O^{max} . By changing the searching sequence of the minimum V_H^{max} and V_O^{max} , there is another version of the bisection algorithm as shown in Algorithm 4.

4.6 Numerical Results and Discussions

We consider an IHWMN that has three types of WMNs N_1 , N_2 , and N_3 . The cell radius in each network is set to $R_1 = 600$ m, $R_2 = 180$ m, and $R_3 = 200$ m, respectively. The total number of logical channels in each network is set to $B_1 = 25$, $B_2 = 5$, and $B_3 = 6$. We assume that the bandwidth of each logic channel of higher bandwidth networks is equal to the bandwidth of 10 logic channels in network N_1 , i.e., $\beta_2 = \beta_3 = 10$. We also set queue size in different network, $Q_1 = 10$ and $Q_2 = Q_3 = 6$. The average call holding times of voice and data calls are set to $E[T_{cV}] = 120$ s and $E[T_{cD}] = 150$ s, respectively.

Figure 4.3 shows the blocking probability of originating voice calls and the forced termination probability of horizontal handoff voice calls with different V_O^{max} . The offered voice traffic load

Algorithm 4 : Pseudocode of optimization algorithm (version 2)

Step 1. Assign a very small positive value to ϵ to check convergence;

Step 2. Set initial value: $V_H^{high} = B_1$, $V_H^{low} = 0$, $V_H^{max} = 0.5(V_H^{high} + V_H^{low})$;

Step 3. $V_O^{high} = V_H^{max}$, $V_O^{low} = 0$, $V_O^{max} = 0.5(V_O^{high} + V_O^{low})$;

Step 4. Use Algorithm 2 to calculate the blocking probability B_{OV} of originating voice calls

and the forced termination probability B_{VH} of handoff voice calls;

Step 5. If $|\frac{B_{OV} - B_{OV}^{th}}{B_{OV} + B_{OV}^{th}}| > \epsilon$, go to step 6; otherwise go to Step 9;

Step 6. If $B_{OV} > B_{OV}^{th}$, go to Step 7; otherwise, go to Step 8;

Step 7. $V_O^{low} = V_O^{max}$, $V_O^{max} = 0.5(V_O^{low} + V_O^{high})$, if $V_H^{max} - V_O^{max} < \epsilon$, go to Step 11; otherwise, go to Step 4;

Step 8. $V_O^{high} = V_O^{max}$, $V_O^{max} = 0.5(V_O^{low} + V_O^{high})$, if $V_O^{max} < \epsilon$, go to step 11; otherwise, go to Step 4;

Step 9. If $|\frac{B_{HHV} - B_{HHV}^{th}}{B_{HHV} + B_{HHV}^{th}}| > \epsilon$, go to Step 10; otherwise, go to Step 13;

Step 10. If $B_{HHV} > B_{HHV}^{th}$, go to Step 11; otherwise, go to Step 12;

Step 11. $V_H^{low} = V_H^{max}$, $V_H^{max} = 0.5(V_H^{low} + V_H^{high})$, if $B_1 - V_H^{max} < \epsilon$, go to Step 14; otherwise go to Step 3;

Step 12. $V_H^{high} = V_H^{max}$, $V_H^{max} = 0.5(V_H^{low} + V_H^{high})$, go to Step 3;

Step 13. End and return V_H^{max} and V_O^{max} ;

Step 14. End without proper V_H^{max} and V_O^{max} .

Figure 4.3: Performances of voice traffic with different V_O^{max}

($\lambda_{OV}E[T_{cV}]$) is 12, and the offered data traffic load ($\lambda_{OD}E[T_{cD}]$) is 15. With the increase V_O^{max} , the blocking probability of originating voice calls becomes less. For fixed V_O^{max} , the forced termination probability of horizontal handoff voice calls improves significantly when V_H^{max} increase. It is obvious that larger V_O^{max} and V_H^{max} can provide better performances for voice traffic. However, larger V_O^{max} and V_H^{max} result in deterioration of data traffic. Figure 4.4 shows that the blocking probability of originating data calls becomes larger when V_O^{max} and V_H^{max} increase. Figure 4.5 shows that the average delay becomes longer when V_O^{max} and V_H^{max} increase. Therefore, we have to find the suitable V_O^{max} and V_H^{max} to provide the best service for data traffic.

In the following, we examine the system performances under our optimum V_O^{max} and V_H^{max} . The total offered traffic load is set to 27. The QoS requirements of voice traffic are set to $B_{OV}^{th} = 5\%$ and $B_{HHV}^{th} = 2\%$. Figure 4.6 shows the optimum V_O^{max} and V_H^{max} when the offered

Figure 4.4: B_{ODA_1} with different V_O^{max}

	Set 1	Set 2	Set 3
V_O^{max}	12.6	16.5	20.2
V_H^{max}	14.6	19.1	21.2

Table 4.2: The set of V_H^{max} and V_O^{max}

voice traffic load increases. When there are more voice calls arriving, larger V_O^{max} and V_H^{max} are needed to satisfy the guaranteed QoS requirements of voice traffic. When the offered voice traffic load is low, no preemption is required to achieve the guaranteed QoS requirement. As a result, V_O^{max} and V_H^{max} are equal to 0.

In order to compare the performances of voice traffic using optimum set of V_O^{max} and V_H^{max} with other sets, we define three sets of V_O^{max} and V_H^{max} as shown in Table 4.2. Figure 4.7 shows the performances of voice traffic using different sets of V_O^{max} and V_H^{max} . Only Set 3 and

Figure 4.5: Average delay of data calls with different $V_O^{\max}$

the optimum set can provide the guaranteed B_{OV}^{th} and B_{HHV}^{th} under any offered voice traffic load. When using optimum set, the blocking probability of originating voice calls and the forced termination probability of horizontal handoff calls are not larger than the guaranteed values, i.e., B_{OV}^{th} and B_{HHV}^{th} . In low traffic load, Set 2 can only provide guaranteed B_{OV}^{th} and B_{HHV}^{th} . QoS requirements of voice traffic cannot be met by Set 1 since the forced termination probability of horizontal handoff voice calls is larger than B_{HHV}^{th} under any offered voice traffic load.

Figures 4.8 and 4.9 show the performances of data traffic. Although Set 3 can provide the better service for voice traffic than other sets, it achieves the worst blocking probability of originating data calls and the average delay. Set 1 provides the best service for data traffic as shown in Figures 4.8 and 4.9. However, it cannot provide satisfied service for voice traffic. Compared to Set 2, the optimum set achieves better performances of data traffic when both of them satisfy the QoS requirements of voice traffic. Therefore, the optimum set can provide the

Figure 4.6: Optimum $V_O^{\max}$ and $V_H^{\max}$

best service for data traffic while satisfying the QoS requirements for voice traffic.

4.7 Summary

In this chapter, we proposed a resource management scheme that can efficiently support voice and data traffic in an IHWMN. The proposed scheme took advantages of service features of different types of WMNs, moving nature of mobile users, and distinct QoS requirements of different types of traffic. An optimization algorithm that can solve the fairness issue between voice and data traffic was proposed. Our results showed that the proposed scheme can achieve the best performance of data traffic while satisfying the QoS requirements of voice traffic.

Figure 4.7: Performances of voice traffic with different offered voice traffic load

Figure 4.8: B_{ODA_1} with different offered voice traffic load

Figure 4.9: Average delay of data calls with different offered voice traffic load

Chapter 5

Traffic-based and Q-learning-based Resource Management Schemes

5.1 Introduction

In this chapter, we propose two resource management schemes from different perspectives to support multiple traffic. The first scheme is traffic-based resource management scheme (TRMS), which allocates resources based on type of traffic (e.g., voice, video, or data), type of call (e.g., originating call or handoff call), network availability, and bandwidth provision.

Since the resource management process in WMNs can be formulated as a Markov decision process (MDP), approaches for MDP can be applied to conduct the resource management in WMNs. In [55], the authors have proposed to apply temporal reinforcement learning techniques to achieve the optimal dynamic channel allocation in cellular networks. Their results show that the performance of temporal reinforcement learning approach is better than the fixed channel al-

location scheme and the best dynamic channel allocation schemes in their literature. In [56], the authors have applied Q-learning approach to achieve the optimal resource allocation in mobile communication systems. The numerical results in [56] show that their proposed channel allocation scheme can achieve similar system performance to the existing optimal dynamic channel allocation scheme using much lower computational complexity. In [57], the authors have proposed to use Q-learning approach to control multi-rate transmission in the multimedia WCDMA systems. The target of the proposed Q-learning approach in [57] is to achieve the optimal resource utilization under some QoS constraints. The simulation results show that their resource management approach can improve the system throughput significantly compared to one conventional interference-based approach. In [58], the prioritized resource allocation in WMNs is addressed using the temporal difference learning and Q-learning approach. For single type of traffic with handoff calls, the results show that Q-learning approach achieves comparative performance to the optimal guard threshold scheme. In this chapter, we propose to formulate the resource management scheme in IHWMNs as a MDP. Then we apply the Q-learning approach and propose the Q-learning-based resource management scheme (QRMS).

This chapter is organized as follows. In the next section, the system model with three types of traffic (i.e., voice, video, and data) is introduced. a TRMS to support multiple traffic is described in Section 5.3. In Section 5.4, the resource management scheme is modeled as a MDP and the QRMS is proposed. In Section 5.5, we evaluate and compare the performance of both resource management schemes through extensive simulations. Finally, we conclude this chapter in Section 5.6.

5.2 System Model

In this chapter, we consider an IHWMN having M different types of WMNs similar to the system model in Chapter 4. Each bandwidth unit in network N_i ($1 \leq i \leq M$) is considered as one logic channel in this chapter and each cell of network N_i ($1 \leq i \leq M$) is assumed to have total B_i logic channels. However, a logic channel in different type of network may have different bandwidth provision. The bandwidth of each logic channel in network N_1 is defined as *one basic bandwidth unit* (BBU). Note that the bandwidth of one logic channel in a higher bandwidth network N_i ($2 \leq i \leq M$) is much larger than one BBU. We define that the bandwidth BW_i ($2 \leq i \leq M$) of one logic channel in network N_i is equal to β_i BBUs, where $\beta_i > 1$.

There are three different types of traffic in our system that have different bandwidth requirements. Voice traffic requires at least B^{vc} BBUs. Video traffic requires at least B_{min}^{vd} BBUs, where $B_{min}^{vd} > B^{vc}$. In other words, a voice or video call can be accepted by a network if the bandwidth provided can satisfy its minimum bandwidth requirement. For example, a voice call can be accepted by network N_1 if network N_1 can provide B^{vc} BBUs to the call. Similarly, a video call can be accepted by network N_1 if network N_1 can provide B_{min}^{vd} BBUs to the call. Voice and video calls can also be accepted by other networks N_i ($2 \leq i \leq M$) if the minimum bandwidth requirements are met. On the other hand, voice and video traffic have different service features. Although voice traffic can be served by a high bandwidth network N_i ($2 \leq i \leq M$), the high bandwidth provision does not improve the service quality of the voice call. On the contrary, the service quality can be improved if more bandwidth is allocated to a video call. In modern communication networks, video traffic may have multiple levels of coding formats that correspond to different bandwidth availability and different levels of service qualities. If more bandwidth is allocated, higher resolution image will be transmitted and better QoS will be

obtained. Therefore, if the available bandwidth is more than B_{min}^{vd} , the quality of video traffic can be improved. However, the quality cannot be improved endlessly. The highest bandwidth requirement in multiple levels of coding formats determines the best video quality, which is denoted as B_{max}^{vd} BBUs. Such difference results in different resource management policies for voice and video traffic. Additionally, from user's point of view, the termination of an ongoing voice (or video) call is more frustrating than blocking a new voice (or video) request. Therefore, some priority should be given to ongoing voice (or video) calls compared to originating voice (or video) calls.

Data traffic is non-real-time and bandwidth-sensitive, which is totally different to voice and video traffic. We assume that a data call requires at least B_{min}^{da} BBUs. However, a data call prefers more bandwidth because higher bandwidth provision can significantly increase the throughput of the data calls and reduce its session time. Therefore, data calls benefit from high bandwidth network. Another feature of data calls is their delay-insensitivity. We assume that there is a queue in each cell of network N_1 . When a data call, either originating or handoff data call, arrives, it is put into the queue if there is no enough resource in the system. When the resource becomes available, it may be allocated to the data calls in the queue.

5.3 Traffic-based Resource Management Scheme (TRMS)

In this section, we introduce a TRMS to support the triple traffic in an IHWMN. Based on the bandwidth requirements of different types of traffic and their delay sensitivities, we propose different network selection strategies and vertical handoff policies for them. Before we explain TRMS in details, we introduce several parameters used in this scheme.

As mentioned in Section 5.2, ongoing voice and video calls require higher priority than

originating voice and video calls. Therefore, a threshold B_{th}^{rt} is set to differentiate originating voice (or video) calls and ongoing voice (or video) calls. B_{th}^{rt} bandwidth units are reserved exclusively for handoff real-time calls. Therefore, a handoff voice (or video) call is accepted if the number of free bandwidth units is not less than B^{vc} (or B_{min}^{vd}). For an originating voice (or video) call, it is accepted by network N_1 if the number of free bandwidth units is not less than $B_{th}^{rt} + B^{vc}$ (or $B_{th}^{rt} + B_{min}^{vd}$). Otherwise, it is blocked. In the next, we described TRMS for each type of traffic.

5.3.1 TRMS for Voice Traffic

Since voice traffic is delay-sensitive and only requires low bandwidth, we assume that a voice call, either originating or handoff voice call, tries lower bandwidth network first. TRMS for voice traffic is described in the following.

- When an originating voice call is generated in area A_1 that is only covered by network N_1 , it is accepted by network N_1 if the number of free bandwidth units in network N_1 is not less than $B_{th}^{rt} + B^{vc}$. Otherwise, the originating voice call is blocked and removed from the system immediately.
- When an originating voice call is generated in area A_i ($2 \leq i \leq M$) that is covered by more than one network, it will be accepted by network N_1 if the number of free bandwidth units is not less than $B_{th}^{rt} + B^{vc}$. Otherwise, it tries other higher bandwidth networks. It is accepted by another available network that has free bandwidth and the lowest bandwidth provision.
- When a horizontal handoff voice call arrives from a neighboring cell of network N_1 , or a vertical handoff voice call arrives from network N_i ($2 \leq i \leq M$), it is accepted by network

N_1 if the number of free bandwidth units is not less than B^{vc} . Otherwise, the ongoing voice call is forcedly terminated.

- When an active voice user moves out of the current cell of network N_1 , the occupied bandwidth in network N_1 is released. When an active voice user completes the communication before moving out of the current cell of network N_1 , the occupied bandwidth in network N_1 is also released. The released bandwidth can be reallocated to the data calls in the queue depending on the resource management scheme for data traffic.
- When an active voice user moves from area A_1 to area A_i ($2 \leq i \leq M$), the ongoing voice call keeps its connection with network N_1 which means no vertical handoff request is generated. When an active voice user of network N_i ($2 \leq i \leq M$) moves out of area A_i , a vertical handoff voice request is generated. If there is enough free bandwidth in network N_1 , the handoff request is granted and the ongoing voice call is accepted by network N_1 . Otherwise, it tries other available networks.

Since higher bandwidth provision does not improve the quality of voice traffic, a voice call is better to be accepted by a low bandwidth network with the large area coverage. The benefit of doing this is that the probability of forced termination decreases due to the reduced number of handoff.

5.3.2 TRMS for Video Traffic

Video traffic is similar to voice traffic because both of them are delay-sensitive. Therefore, an originating or handoff video call is blocked or terminated if there is no enough free bandwidth that can be allocated to it. On the other hand, a video call requires more bandwidth than a voice call. Furthermore, the quality of video traffic can be improved if more bandwidth can be

allocated. However, the quality of video calls cannot be improved if the allocated bandwidth is already larger than B_{max}^{vd} . Based on the above assumptions, TRMS for video traffic is described in the following.

- If an originating video call is generated in area A_1 that is only covered by network N_1 , it is accepted by network N_1 if the number of free bandwidth units in network N_1 is not less than $B_{th}^{rt} + B_{min}^{vd}$. Otherwise, the originating video call is blocked.
- If an originating video call is generated in an overlapped area A_i ($2 \leq i \leq M$) that is covered by more than one network, the bandwidth provision of all available networks need to be checked. All the available networks with enough free bandwidth are sorted in a candidate network list from the highest to the lowest bandwidth provision. The network that provides the best quality with the least amount of bandwidth wastage will be selected. For example, we assume that there are two adjacent candidate networks N_i and N_j , in the sorted candidate network list, where their bandwidth provision has $BW_i > B_{max}^{vd} > BW_j$. The originating video call is accepted by network N_i since network N_i provides better quality than network N_j . The networks in the candidate network list that have higher bandwidth provision than network N_i are not selected because they provide the same quality as network N_i but lower bandwidth utilization. The networks in the candidate network list that have less bandwidth provision than network N_i are not selected because they provide worse quality. If all the candidate networks cannot provide bandwidth which is larger than B_{max}^{vd} , the originating video call is accepted by the network which provides the highest bandwidth provision. If all the available high bandwidth networks do not have enough free bandwidth, the originating video call tries network N_1 . If the number of free bandwidth units in network N_1 is not less than $B_{th}^{rt} + B_{min}^{vd}$, the originating video call is

accepted by network N_1 . Otherwise, the originating video call is blocked.

- When an active video user moves from a neighboring cell of network N_1 , or moves from another network N_i ($2 \leq i \leq M$) to network N_1 , a vertical handoff video request is generated. The vertical handoff video call is accepted by network N_1 if the number of free bandwidth units in network N_1 is not less than B_{min}^{vd} . Otherwise, it is forcedly terminated.
- When an active video user moves from area A_1 to area A_i ($2 \leq i \leq M$) that is covered by more than one network, the ongoing video call tries higher bandwidth networks. If the bandwidth provision of a high bandwidth network is larger than B_{min}^{vd} , the ongoing video call is switched to high bandwidth network. If there are more than one high bandwidth network available, the ongoing video call is accepted by the network which provides the best quality with the least amount of bandwidth wastage.
- If an active video user moves out the current cell of network N_1 , the occupied bandwidth is released and can be reallocated to data calls waiting in the queue according to TRMS for data traffic. If an active video user completes the communication before moving out of the current cell of network N_1 , the occupied bandwidth is also released and can be reallocated to data calls in the queue.

Similar to voice traffic, some priority is given to handoff video calls for both horizontal and vertical handoff video calls. However, unlike voice traffic, video traffic is bandwidth-sensitive since higher bandwidth can improve the quality. Due to the feature of multiple levels of coding formats, the service quality cannot be improved unlimitedly. Therefore, it is not necessary to request higher bandwidth provision if the service quality has already reached the best level.

5.3.3 TRMS for Data Traffic

The above TRMS focused on real-time traffic. As a non-real-time traffic, data traffic is delay-insensitive. When a data call, either originating or handoff data call, arrives, it is put into the queue if there is not enough bandwidth available. Furthermore, higher bandwidth can significantly increase the throughput of data calls and reduce their session time. Therefore, TRMS for data traffic is described in the following.

- If an originating data call is generated in area A_1 that is only covered by network N_1 , it is accepted by network N_1 if the number of free bandwidth units in network N_1 is not less than $B_{th}^{rt} + B_{min}^{da}$. Otherwise, the originating data call is put into the queue.
- If an originating data call is generated in area A_i ($2 \leq i \leq M$) that is covered by more than one network, all the available networks with free bandwidth are sorted in a candidate network list from the highest to the lowest bandwidth provision. The originating data call is accepted by the network that has the highest bandwidth provision in the candidate network list. If all available high bandwidth networks do not have free bandwidth, the originating data call tries network N_1 . If the number of free bandwidth units in network N_1 is not less than $B_{th}^{rt} + B_{min}^{da}$, the originating data call is accepted by network N_1 . Otherwise, the originating data call is put into the queue.
- When an active data user moves from a neighboring cell of network N_1 to the current cell, the ongoing data is accepted by network N_1 if the number of free bandwidth units in network N_1 is not less than $B_{th}^{rt} + B_{min}^{da}$. Otherwise, the ongoing data call is put into the queue.
- When an active data user moves, the user keeps searching for a network with a higher

bandwidth provision. If another network with a higher bandwidth provision that has free bandwidth is found, this ongoing data call is switched to the higher bandwidth network. If there is no higher bandwidth network having free bandwidth, the ongoing data call keeps the connection with its current serving network before moving out of the current network.

- We consider an active data user who is connected with a high bandwidth network N_i ($2 \leq i \leq M$). When the active data user moves out of area A_i that is covered by network N_i , a vertical handoff request is generated. All the available networks with free bandwidth are sorted in a candidate network list from the highest to the lowest bandwidth provision. The ongoing data call is accepted by the network which has the highest bandwidth provision in the candidate network list. If there is no high bandwidth network having free bandwidth, the ongoing data call tries network N_1 . If the number of free bandwidth units in network N_1 is not less than $B_{th}^r + B_{min}^{da}$, the ongoing data call is accepted by network N_1 . Otherwise, the ongoing data call is put into the queue.
- We consider a data call waiting in the queue. If this active user moves into an area that is covered by other networks, it checks the bandwidth availabilities of the new networks. If there are available networks having free bandwidth, this data call is accepted by the network that has the highest bandwidth provision.

For data traffic, the originating data calls and ongoing data calls are treated equally, which is different to voice and video traffic. If there is no enough bandwidth available, the data call is put into the queue to wait for available resource.

Figure 5.1 shows how TRMS works in our proposed system. A traffic-based resource management module is implemented to allocate bandwidth to all types of calls in different types of networks. When a call is generated, the traffic-based resource management module checks its

Figure 5.1: Traffic-based resource management scheme (TRMS)

traffic type (e.g., voice, video, or data), call type (e.g., originating call, horizontal handoff call, or vertical handoff call), network availability and their bandwidth provision. Then, the traffic-based resource management module makes a decision to accept the call in a suitable network or to decline the call. In TRMS, we can see that different types of traffic are treated differently. Even for the same type of real-time traffic, the originating calls and ongoing calls are treated differently to give higher priority to ongoing real-time calls.

In the next section, we use MDP to model the resource management scheme and propose another resource management scheme, Q-learning-based Resource Management Scheme (QRMS).

5.4 Q-learning-based Resource Management Scheme (QRMS)

Q-learning is a reinforcement learning technique that can be used to solve Markov decision problem (or process) [59]. Since the resource management scheme can be naturally formulated

as a Markov decision process, we propose to apply Q-learning approach to conduct the resource management in IHWMNs. In the following, we first introduce the Markov decision process and the Q-learning approach. Then, we formulate the resource management scheme as a Markov decision process and propose QRMS to support voice, video, and data traffic in IHWMNs.

5.4.1 Markov Decision Process and Q-learning Approach

Markov decision process [60] is used to model a wide range of optimization problems in the fields of industry control, artificial intelligence, and economic decision modeling. In general, Markov decision process can be characterized by the following four elements.

- *State Space: S .* The state space S includes all the valid system states s where $s \in S$;
- *Decision Space: A .* The decision space A includes all the available decisions (or actions) a where $a \in A$. In each state, the available decisions may be different.
- *State Transition Probability: $P_a(s, s') = P(s_{t+1} = s' | s_t = s, a_t = a)$.* In any state s_t at time t , the decision maker has to select one of the available decisions a_t . After the decision has been made, the system state may change to another state s'_{t+1} with the state transition probability $P_a(s, s') = P(s_{t+1} = s' | s_t = s, a_t = a)$.
- *Reward: r .* In each state, the decision maker obtains an instant reward r that is associated with the decision being made. Different decisions generally result in different rewards.

Clearly, the decision maker has to make a decision when an event happens. In general, there are several decision options available to select. The decision maker selects one of the available decisions and receives an instant reward. After the decision has been made, the system state

evolves from the current state to another state. The name of Markov decision process comes from the Markov property of the decision process because the next system state only depends on the current system state and the selected decision. The next system state is independent of the system states before the current system state. However, compared to a traditional Markov chain, Markov decision process has two additional features: decision and reward. Usually, there is a function of the reward, such as the cumulative reward and the discount reward, to characterize different problems. The aim of the decision selection is to maximize such function of the reward.

A policy in the Markov decision process is a mapping from state space to decision space. The policy space consists of all the valid system states and their associated decisions. The optimal decision can be presented as a policy and the decision maker will follow the optimal policy to select a decision at each decision epoch. Obviously, the optimal policy of the Markov decision process can be obtained by going through all the policies in the policy space. However, the policy space increases exponentially with the size of the state space and the decision space. Therefore, such approach becomes impossible for a Markov decision process with large state space and decision space.

Dynamic programming and reinforcement learning are two approaches that are commonly used to solve such Markov decision process. Dynamic programming approach can find the optimal policy through value iteration or policy iteration. However, it requires all the information about the system to be known, which includes all the transition probabilities. Therefore, it does not work for those decision problems that the full knowledge of the system is unknown. On the contrary, the reinforcement learning is another approach that is model-free. It achieves the optimal decision through the interaction between the decision maker and the dynamically changing environment.

Q-learning algorithm, one of the reinforcement learning algorithms, learns the value of function $Q(s, a)$ to find the optimal decision policy. Compared to dynamic programming approach, Q-learning approach has two advantages. Firstly, Q-learning approach is model-free. Therefore, Q-learning approach does not require the full knowledge of state transition probabilities of the dynamic environment. Furthermore, it can adapt to the changes of the environment. Secondly, the computational complexity of Q-learning approach is much less than traditional dynamic programming approaches, since a traditional dynamic programming approach needs two memory structures, one for function evaluation and the other for the policy. On the other hand, Q-learning approach only requires the memory for the Q-value.

There are different methods to represent the Q-value. The most straightforward method is to use a table. When the decision maker needs to make a decision, it checks the table to find the related Q-value of each decision in the current system state and selects the decision with the highest Q-value. Then, the related Q-value in the table is updated after a decision has been made. In some situations, the problem space may be too large to fit in the table. In these cases, the neural network is used to represent the Q-value with an additional training process [56]. In this paper, we use a table to store the Q-value.

5.4.2 QRMS for Voice, Video, and Data Traffic

The system state is represented as a M -tuple of non-negative integers $(b_1, b_2, \dots, b_M)$, where b_i ($1 \leq i \leq M$) is the number of occupied bandwidth units in network N_i . If we denote the number of voice calls, the number of video calls, and the number of data calls in network N_i as n_i^{vc} , n_i^{vd} , and n_i^{da} for $1 \leq i \leq M$, the system state is given by $(n_1^{vc} B^{vc} + n_1^{vd} B_{min}^{vd} + n_1^{da} B_{min}^{da}, n_2^{vc} + n_2^{vd} + n_2^{da}, \dots, n_M^{vc} + n_M^{vd} + n_M^{da})$.

In our system, a decision needs to be made when an event happens such as new call and handoff call generation. Once the decision has been made, a reward that is associated with that decision is obtained. The system state also transits from the current state to another state. All the events that require a decision and their associate rewards are described as follows.

- *Event (a): Originating voice call arrival in area A_1 .*

There are two decisions available. The originating voice call can be accepted by network N_1 with a reward, or rejected with zero reward.

- *Event (b): Originating voice call arrival in area A_i ($2 \leq i \leq M$).*

There are multiple decisions available. The originating voice call can be accepted by one of the available networks with an associated reward, or rejected with zero reward. It is to note that a larger reward will be granted if the originating call is accepted by network N_1 because a voice call prefers a low bandwidth network with the large area coverage.

- *Event (c): Horizontal handoff voice call arrival.*

There are two decisions available. The horizontal handoff call can be accepted by network N_1 with a reward, or rejected with zero reward. It is to note that the reward granted should be larger than the reward granted for accepting an originating voice call since terminating a handoff voice call is more frustrating than blocking an originating voice call. By using larger reward, the horizontal handoff voice calls are given a higher priority than originating voice calls.

- *Event (d): Vertical handoff voice call arrival.*

Vertical handoff can be categorized as DVH (downward vertical handoff) and UVH (upward vertical handoff). For DVH, the ongoing voice call may be switched to another network with zero reward or stay with the current serving network with a reward. For

UVH, the ongoing voice call can be accepted by one of other available networks with an associated reward, or rejected with zero reward.

- *Event (e): Originating video call arrival in area A_1 .*

There are two decisions available. The originating video call can be accepted by network N_1 with a reward, or rejected with zero reward.

- *Event (f): Originating video call arrival in area A_i ($2 \leq i \leq M$).*

Multiple decisions are available for this event. The originating video call can be accepted by one of the available networks with an associated reward, or rejected with zero reward.

All candidate networks will be sorted in a candidate network list from the highest to the lowest bandwidth provision. Among the networks whose bandwidth are larger than B_{max}^{vd} , the associated reward increases when the bandwidth provision decreases. Among the networks whose bandwidth provision are smaller than B_{max}^{vd} , the associated reward decreases when the bandwidth provision decreases.

- *Event (g): Horizontal handoff video call arrival.*

There are two decisions available. The horizontal handoff video call can be accepted by network N_1 with a reward, or rejected with zero reward. It is to note that the reward granted should be larger than the reward granted for accepting an originating video call similar to voice traffic.

- *Event (h): Vertical handoff video call arrival.*

For DVH, the ongoing video call can be accepted by another available network with an associated reward or stay with the current serving network with zero reward. For UVH, the ongoing video call can be accepted by another network with an associated reward or rejected with zero award. All candidate networks can be sorted in a candidate network list

from the highest to the lowest bandwidth provision. Among the networks whose bandwidth provision are larger than B_{max}^{vd} , the associated reward increases when the bandwidth provision decreases. Among the networks whose bandwidth provision are smaller than B_{max}^{vd} , the associated reward decreases when the bandwidth provision decreases.

- *Event (i): Originating data call arrival in area A_1 or handoff data call arrival.*

There are two decisions available. The data call, either originating or handoff data call, can be accepted by network N_1 with a reward, or put into the queue with zero reward. It is to note that accepting an originating or handoff data call results in the same reward, which indicates that they are treated equally.

- *Event (j): Originating data call arrival in area A_i ($2 \leq i \leq M$).*

Multiple decisions are available. The originating data call can be accepted by one of the available networks with an associated reward or put into the queue with zero reward. All the candidate networks can be sorted in a candidate network list from the highest to the lowest bandwidth provision. The reward increases when the bandwidth provision increases, where the network with the highest bandwidth provision has the highest reward.

- *Event (k): DVH data calls.*

Multiple decisions are available for this event. If there are higher bandwidth networks available with free bandwidth, the ongoing data call is switched to the higher bandwidth network with an associated reward. It is also possible that the ongoing data call stays in the current serving network with zero reward.

- *Event (l): Data calls waiting in the queue arrival to new networks.*

Multiple decisions are available if more than one new network with free bandwidth are available. The data call in the queue can be removed from the queue and accepted by one

of the new networks with an associated reward (a higher reward is granted if accepted by a network with higher bandwidth provision). It is also possible that the data call stays in the queue with zero reward.

- *Event (m): Ongoing call completion or out of cell.*

There are two decisions available. The released bandwidth can be reallocated to data calls in the queue with a reward, or no reallocation is conducted with zero reward.

The Q-value can be characterized by $Q(s, a)$ for each state s and each available decision a . The optimal policy is to select the decision π_t that has the largest Q-value at each decision epoch t , which is given by

$$\pi_t = \max_{a_t \in A} Q(s_t, a_t). \quad (5.1)$$

The rule to update the Q-value is given by

$$Q_t^{new}(s_t, a_t) \leftarrow Q_t^{old}(s_t, a_t) + \alpha[r_t + \gamma \max_{a_{t+1} \in A} Q_t^{old}(s_{t+1}, a_{t+1}) - Q_t^{old}(s_t, a_t)], \quad (5.2)$$

where α ($0 \leq \alpha \leq 1$) is the learning rate, γ ($0 \leq \gamma < 1$) is the discounted factor. By combining $Q_t^{old}(s_t, a_t)$, Equation (5.2) can be rewritten as

$$Q_t^{new}(s_t, a_t) \leftarrow (1 - \alpha)Q_t^{old}(s_t, a_t) + \alpha[r_t + \gamma \max_{a_{t+1} \in A} Q_t^{old}(s_{t+1}, a_{t+1})]. \quad (5.3)$$

It is obvious that the current Q-value plays a role when updating the Q-value table. We denote the Q-value at time t as $Q_t(s, a)$. In [61], the authors have shown that $Q_t(s, a)$ can converge to $Q^*(s, a)$ with probability 1 as $t \rightarrow \infty$ under some conditions, where each $Q(s, a)$ can be visited infinitely often and the learning rate decreases to 0.

In our system, QRMS is implemented by a Q-learning module. The Q-learning module consists of two parts, the Q-value table and the decision engine. The Q-value table is used to

store the Q-value for each pair of state and decision. The decision engine accesses the Q-value table and makes a decision. Then, it updates the related Q-value. Figure 5.2 shows how QRMS works in our system.

Figure 5.2: Q-learning-based resource management scheme (QRMS)

5.5 Numerical Results and Discussions

In this section, we will evaluate the system performance of the proposed TRMS and QRMS. As an example, we consider a cell of network N_1 that covers two higher bandwidth networks N_2 and N_3 . The radius of each network is set to $R_1 = 550m$, $R_2 = R_3 = 200m$. The number of bandwidth units in each network is set to $B_1 = 22$ and $B_2 = B_3 = 4$, respectively. Additionally, B_{th}^{rt} is set to 2 in TRMS, which means 2 BBUs in network N_1 are exclusively reserved for handoff voice and video calls. The bandwidth BW_i ($i = 2, 3$) of each bandwidth unit in network N_i ($i = 2, 3$) is equal to $\beta_i = 10$ ($i = 2, 3$) BBUs.

The bandwidth requirement of voice traffic is set to $B^{vc} = 1$ BBU. The minimum bandwidth requirement of video traffic is set to $B_{min}^{vd} = 2$ BBUs, and the maximum bandwidth requirement of video traffic is set to $B_{max}^{vd} = 4$ BBUs. A video call, either originating or handoff video call, tries higher bandwidth network first if a higher bandwidth network N_2 or N_3 is available. The minimum bandwidth requirement of data traffic is set to $B_{min}^{da} = 1$ BBU. Similar to video traffic, a data call tries a higher bandwidth network first if a higher bandwidth network is available.

The arrival processes of voice, video, and data traffic, either originating or horizontal handoff arrival processes, are assumed to be Poisson processes. We use λ_O^{vc} , λ_O^{vd} , and λ_O^{da} to denote the average arrival rates of originating voice, video, and data calls, respectively. We also use λ_{HH}^{vc} , λ_{HH}^{vd} , and λ_{HH}^{da} to denote the average arrival rate of horizontal handoff voice, video, and data calls. The call holding times of all types of calls are assumed to follow exponential distributions. The average call holding times of voice, video, and data calls are set to $E[T_c^{vc}] = 120s$, $E[T_c^{vd}] = 180s$, and $E[T_c^{da}] = 150s$, respectively. Table 5.1 summaries the parameters used in our simulations, where the arrival rates vary in the simulations. The discounted factor γ in QRMS is set to 0.8 and the rewards used in the simulations are summarized in Table 5.2.

First of all, we examine the system performance when the traffic load of originating voice calls changes. The traffic load of originating voice calls is defined as $\lambda_O^{vc} E[T_c^{vc}]$. The average arrival rates of originating video calls, originating data calls, horizontal handoff voice calls, horizontal handoff video calls, and horizontal handoff data calls are set to $\lambda_O^{vd} = 0.04$, $\lambda_O^{da} = 0.04$, $\lambda_{HH}^{vc} = 0.02$, $\lambda_{HH}^{vd} = 0.02$, and $\lambda_{HH}^{da} = 0.02$, respectively. We denote the blocking probabilities of voice calls in the whole area as B_O^{vc} , the blocking probabilities of voice calls in area A_1 as $B_{O_{A_1}}^{vc}$, and the forced termination probability of horizontal handoff voice calls as B_{HH}^{vc} . Figure 5.3 shows that $B_{O_{A_1}}^{vc}$ is larger than B_{HH}^{vc} in TRMS since B_{th}^{rt} bandwidth units are exclusively

λ_O^{vc}	Arrival rate of originating voice traffic	varied
λ_O^{vd}	Arrival rate of originating video traffic	varied
λ_O^{da}	Arrival rate of originating data traffic	varied
λ_{HH}^{vc}	Arrival rate of horizontal handoff voice traffic	varied
λ_{HH}^{vd}	Arrival rate of horizontal handoff video traffic	varied
λ_{HH}^{da}	Arrival rate of horizontal handoff data traffic	varied
$E[T_c^{vc}]$	Average call holding time of voice traffic	120 s
$E[T_c^{vd}]$	Average call holding time of video traffic	180 s
$E[T_c^{da}]$	Average call holding time of data calls if serviced by network N_1	150 s
R_1	Cell radius of network N_1	550 m
R_i ($i = 2, 3$)	Cell radius of network N_i ($i = 2, 3$)	200 m
B_1	Total number of bandwidth units in network N_1	22
B_i ($i = 2, 3$)	Total number of bandwidth units in network N_i ($i = 2, 3$)	4
β_i ($i = 2, 3$)	The bandwidth of each bandwidth unit in network N_i ($i = 2, 3$)	10 BBUs
B^{vc}	Bandwidth requirement of voice traffic	1 BBU
B_{min}^{vd} and B_{max}^{vd}	The minimum and maximum bandwidth requirements of video traffic	2 and 4 BBUs
B_{min}^{da}	The minimum bandwidth requirement of data traffic	1 BBU

Table 5.1: System configuration of simulations

Reward for accepting an originating voice call in network N_1	0.5
Reward for accepting an originating voice call in network N_2	0.1
Reward for accepting an originating voice call in network N_3	0.1
Reward for accepting a horizontal handoff voice call in network N_1	1.0
Reward for accepting a video call in network N_1	0.2
Reward for accepting a video call in network N_2	0.6
Reward for accepting a video call in network N_3	0.6
Reward for accepting a horizontal handoff video call in network N_1	1.0
Reward for accepting an originating data call in network N_1	0.1
Reward for accepting an originating data call in network N_2	1.0
Reward for accepting an originating data call in network N_3	1.0

Table 5.2: Reward configuration for QRMS

Figure 5.3: Blocking probability of voice traffic

reserved for real-time handoff calls. In QRMS, the reward for accepting an originating voice call is less than the reward for accepting a horizontal handoff call. Therefore, $B_{OA_1}^{vc}$ is also larger than B_{HH}^{vc} in QRMS. Compared to TRMS, $B_{OA_1}^{vc}$ and B_O^{vc} are much less in QRMS.

Figure 5.4 shows the blocking probability of video calls when the traffic load of originating voice calls changes. We can observe the similar performance as shown in Figure 5.3, where QRMS achieves better performance in the blocking probabilities $B_{OA_1}^{vd}$ and B_O^{vd} in area A_1 and in the whole area. However, TRMS obtains better forced termination probability B_{HH}^{vd} than QRMS.

Figure 5.5 shows the performance of data traffic when the traffic load of originating voice calls changes. We denote the probability that an originating data call being queued in area A_1 as $PQ_{OA_1}^{da}$, the probability that an originating data call being queued in the whole area as PQ_O^{da} , and the probability that a horizontal handoff data call being queued as PQ_{HH}^{da} . In both schemes,

Figure 5.4: Blocking probability of video calls

the originating data calls and handoff data calls, either horizontal handoff or vertical handoff data calls, are treated equally. The originating data calls and handoff data calls share the same resource in TRMS, while accepting both types of calls results in the same reward in QRMS. As a result, $PQ_{OA_1}^{da}$ is equal to PQ_{HH}^{da} as shown in Figure 5.5. Since the originating data calls in overlapped area A_i ($i = 2, 3$) have more chances to obtain the bandwidth, the probability PQ_O^{da} is less than $PQ_{OA_1}^{da}$. Compared to TRMS, QRMS achieves better performance in $PQ_{OA_1}^{da}$, PQ_O^{da} , and PQ_{HH}^{da} .

Finally, the performance of originating voice and video calls are examined for fixed total traffic load. However, the traffic load of originating voice calls increases, while the traffic load of originating video calls decreases at the same time. The total traffic load is fixed to 18. Figure 5.6 shows that QRMS achieves lower blocking probability for both originating voice and video calls than TRMS.

Figure 5.5: Queued probability of data traffic

5.6 Summary

In this chapter, we proposed two resource management schemes TRMS and QRMS from different perspectives. The proposed TRMS conducts the resource allocation based on the traffic types (voice, video, or data), call types (originating call or handoff call), the network availability, and the bandwidth provision. Then, the resource management scheme was formulated as a Markov decision process and QRMS was proposed to conduct the resource allocation. By defining different rewards for accepting different types of traffic to different types of networks, QRMS can also treat each service and network differently. The simulation results showed that QRMS achieves better system performance than TRMS in most system performance.

Figure 5.6: Blocking probability of voice and video calls for fixed offered load

Chapter 6

Conclusions and Future Work

In this thesis, we have proposed network selection strategies and resource management schemes in IHWMNs (integrated heterogeneous wireless and mobile networks) and analyzed their system performance.

Firstly, we briefly reviewed the existing research in IHWMNs. Then, we proposed system models and traffic models for IHWMNs in Chapter 3. Based on the proposed system models and traffic models, we designed a CFNS (cost-function-based network selection) strategy. Unlike most existing network selection strategies which are user-centric, the proposed CFNS strategy is designed based on system's perspective and also considers user's needs. The system performance of the proposed CFNS strategy was analyzed by using theoretical model and extensive simulations. The simulation results verified the theoretical analysis, which showed that the proposed CFNS strategy can achieve a tradeoff between the blocking probability of originating calls and the average received signal strength. This feature is very important for both systems and users, respectively. In Chapter 4, we proposed preemption-based resource management schemes to support voice and data traffic in IHWMNs, which takes advantages of heterogeneities of traffic

and networks, and the moving nature of mobile users. In the proposed preemption scheme, two thresholds were set to differentiate the originating and horizontal handoff voice calls. In order to provide the best service for data traffic and the guaranteed QoS for voice traffic, a bisection algorithm was used to find the suitable thresholds. Finally, two resource management schemes were discussed from different perspectives in Chapter 5. The first scheme is TRMS (traffic-based resource management scheme) that allocates resources based on the traffic type, call types, the network availability, and the bandwidth provision. In the second scheme, the resource management scheme was formulated as a MDP (Markov decision process) and the Q-learning approach was applied to allocate the resource. Extensive simulation were conducted to validate and compare the proposed two resource management schemes.

In the next generation wireless and mobile networks (Beyond 3G or 4G), cellular networks still play a major role due to their dominant market share and good service quality. Other types of networks, such as WiMax and WLAN, are also witnessing fast deployment. However, any single type of WMN cannot always provide the “best” service for every mobile user everywhere. Network integration is a promising choice to offer the “best” service. Based on the type of user’s service request and network availability, the mobile user can obtain the “best” service from IHWMNs. However, such integration still faces a lot of challenges as follows:

- *Adjustment of bandwidth allocation in IHWMNs:* In the IHWMN, different types of WMN have different bandwidth provision. On the other hand, different types of traffic have different bandwidth requirements. Therefore, the users may experience unstable QoS when the vertical handoff happens frequently. Some bandwidth adjustment or smoothing algorithms are required to make the transition smooth and achieve more stable QoS.
- *Application of bandwidth splitting in IHWMNs:* Some applications have very high band-

width requirement, like Internet TV. As a result, any single type of WMN may not support such high bandwidth application very well. Bandwidth splitting is an approach to solve this problem, where the whole bandwidth requirement is divided into several parts and different parts are serviced by different types of WMNs. However, such splitting approach brings a lot of issues, such as bandwidth splitting strategies and synchronization among different networks. Efficient algorithms are required to provide satisfying services through multiple networks at the same time.

- *Adaptive bandwidth allocation in IHWMNs:* In modern wireless and mobile systems, adaptive bandwidth allocation can be applied to accept more mobile users when the incoming traffic becomes heavy. However, it becomes more difficult when it is applied to support multiple services in IHWMNs. It needs to decide to make a vertical handoff that may cause adaptive bandwidth reallocation, or stay within the current serving networks.
- *Charging model and its effect:* Different types of WMNs have different charging models. For example, some networks charge the access fee based on the amount of traffic, while other networks have the monthly charging plan. Therefore, such diversity of charging models will affect the user's preference. An approach to combine charging models and resource management schemes is emergently required.

Although the IHWMN is a promising candidate for the future WMNs, a lot of issues have to be addressed before its commercial application. Our work has provided a good start to solve the problems in the IHWMN. We believe that the research topics and analytic methods presented in our work will contribute to the research and development of the future IHWMNs.

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