Queueing Networks for Vertical Handover

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To my family

ABSTRACT

It is widely expected that next-generation wireless communication systems will be heterogeneous, integrating a wide variety of wireless access networks. Of particular interest recently is a mix of cellular networks (GSM/GPRS and WCDMA) and wireless local area networks (WLANs) to provide complementary features in terms of coverage, capacity and mobility support. If cellular/WLAN interworking is to be the basis for a heterogeneous network then the analysis of complex handover traffic rates in the system (especially vertical handover) is one of the most essential issues to be considered.

This thesis describes the application of queueing-network theory to the modelling of this heterogeneous wireless overlay system. A network of queues (or queueing network) is a powerful mathematical tool in the performance evaluation of many large-scale engineering systems. It has been used in the modelling of hierarchically structured cellular wireless networks with much success, including queueing network modelling in the study of cellular/WLAN interworking systems. In the process of queueing network modelling, obtaining the network topology of a system is usually the first step in the construction of a good model, but this topology analysis has never before been used in the handover traffic study in heterogeneous overlay wireless networks. In this thesis, a new topology scheme to facilitate the analysis of handover traffic is proposed.

The structural similarity between hierarchical cellular structure and heterogeneous wireless overlay networks is also compared. By replacing the microcells with WLANs in a hierarchical structure, the interworking system is modelled as an open network of Erlang loss systems and with the new topology, the performance measures of blocking probabilities and dropping probabilities can be determined. Both homogeneous and non-homogeneous traffic have been considered, circuit-switched and packet-switched. Example scenarios have been used to validate the models, the numerical results showing clear agreement with the known validation scenarios.

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LIST OF ABBREVIATIONS

2G	Second Generation (mobile network)
3G	Third Generation (mobile network)
3GPP	3G Partnership Project
AP	Access Point
ATM	Asynchronous Transfer Mode
BS	Base Sation
BSC	Base Station Controller
BTS	Base Transceiver Station
CAC	Connection Admission Control
CBR	Case-Based Reasoning
CDMA	Code Division Multiple Access
CN	Core Network
CP	Cut-off Policy
DCF	Distributed Coordination Function
EFPA	Erlang Fixed Point Approximation
FDMA	Frequency Division Multiple Access
FG	Fractional Guard channel policy
GGSN	Gateway GPRS Support Node
GMSC	Gateway MSC
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communication
HCF	Hybrid Coordination Function
HCS	Hierarchical Cellular Structure
IMT-2000	International Mobile Telephony 2000
IID	Independent and Identical-Distributed random variable
IP	Internet Protocol
IS-95	cdmaOne, one of the 2nd generation systems, mainly in America and in Korea
KB	Knowledge Base
MANET	Mobile Ad-hoc NETwork
MS	Mobile Station

MSC	Mobile service Switching Centre
MT	Mobile Terminal
NB	Node-B
OQN	Open Queueing Network
RAN	Radio Access Network
PSTN	Public Switched Telephone Network
PLMN	Public Land Mobile Network
RNC	Radio Network Controller
RNP	Radio Network Planning
RNS	Radio Network Subsystem
RRM	Radio Resource Management
SGSN	Serving GPRS Support Node
SIR	Signal-to-Interference Ratio
SLA	Service Level Agreement
TDMA	Time Division Multiple Access
TD-SCDMA	Time Division Synchronous Code Division Multiple Access
TIA	Telecommunications Industry Association
UE	User Equipment
UMTS	Universal Mobile Telecommunication System
UTRAN	UMTS Radio Access Network
VLR	Visitor Location Register
W-CDMA	Wideband Code Division Multiple Access

LIST OF SYMBOLS

Symbol	Definition
N^c	Total number of the cells
N^w	Total number of the WLANs
C_i^a	Set of cells adjacent to cell i
W_i^o	Set of WLANs inside the coverage of cell i
W_k^a	Set of WLANs adjacent to WLAN k
C_k^o	Set containing the overlaying cell of WLAN k
C_i^c	Capacity of cell i
C_k^w	Capacity of each WLAN k
R_i^c	Reserved channels of cell i
R_k^w	Reserved channels of WLAN k
$\lambda_i^{(c)}$	Total call arrival rate of cell i
$\lambda_i^{(cn)}$	New call arrival rate of cell i
$\lambda_k^{(wn)}$	New call arrival rate of WLAN k
$\lambda_{ji}^{(cc)}$	Horizontal handover rate of adjacent cell j offered to cell i
$\lambda_{lk}^{(ww)}$	Horizontal handover rate of adjacent WLAN l offered to WLAN k
$\lambda_{yj}^{(wc)}$	Vertical handover rate of WLAN y offered to cell j
$\lambda_{yk}^{(cw)}$	Vertical handover rate of cell y offered to cell k
$\lambda_{zj}^{(wo)}$	Overflow traffic rate from WLAN z to the overlaying cell j
$\lambda_{zk}^{(co)}$	Overflow traffic rate from cell z to the inside WLAN k
$B_j^{(c)}$	New call blocking probability in cell i
$D_j^{(c)}$	Handover dropping probability in cell i
$B_k^{(w)}$	New call blocking probability in WLAN k
$D_k^{(w)}$	Handover dropping probability in WLAN k
$H_{ij}^{(cc)}$	Probability to attempt a horizontal handover to adjacent cell j

$H_{ik}^{(cw)}$	Probability to attempt a vertical handover to WLAN k inside cell i
$H_{kl}^{(ww)}$	Probability to attempt a horizontal handover to adjacent WLAN l
$H_{ki}^{(wc)}$	Probability to attempt a vertical handover to overlaying cell i
γ_{zk}	Coverage ratio between WLAN k and overlay cell z

Chapter 1 INTRODUCTION

1.1 Background

With the wide variety of wireless radio access network (RAN) technologies that have been developed during the last decade, there is a lot of interest in next generation wireless networks for enabling different access networks to interoperate with each other as seamlessly as possible. Next-generation wireless communications systems are envisaged to be heterogeneous in nature, with the ability to seamlessly integrate this wide variety of RAN technologies to offer a comprehensive and flexible service to the wireless customers. Among many successfully deployed wireless access networks, the two most promising ones are cellular networks and wireless local area networks (WLANs) as it can be noticed with the two main tracks of the development in the evolution of wireless communication systems. One is led by ITU and 3GPP/3GPP2 emphasizing on providing high quality voice service to mobile users, the other is led by IEEE with an emphasis on easy access of a local area user.

Cellular networks (including various 2G, 3G technologies such as GSM/GPRS, UMTS/WCDMA etc) and wireless local area networks provide very good complementary features in terms of coverage, capacity and mobility support. Thus cellular/WLAN interworking has drawn a lot of attention from both industry and academia as a good candidate for a future integrated wireless solution to provide a better overall network performance of the whole system. Such integration will bring significant benefits to both service providers and end users due to their complimentary characteristics.

Having experienced three generations of evolution, cellular networks originally aimed at providing a high-quality circuit-switched voice service and high mobility support, and they have been well deployed around the world and have evolved into the Third Generation (3G) [WS07]. It can now provide multimedia services with a maximum bit rate of 2 Mb/s. Three major standards for the current 3G mobile/wireless cellular networks are the Universal Mobile Telecommunication System (UMTS), CDMA20000 and TD-SCDMA.

On the other hand WLANs that operate at unlicensed frequency bands were originally aimed at providing relatively high rate data services with lower cost and have shown their potential to be feasible candidates for high-rate data service provisioning at hotspot areas with low user mobility. Most successful players in this group are all from IEEE 802.11 family including IEEE 802.11a, IEEE 802.11b and of course the mainstream product for laptop computers IEEE 802.11g and the coming IEEE 802.11n.

The majority of current research on cellular/WLAN interworking focuses on relatively high-level issues such as the integration architecture [AS04], [MCFC05]. The system is often studied from the perspectives of access control, mobility management, security and billing etc. Another research focus of cellular/WLAN integration is the issue of RAN (Radio Access Network) selection and handover decision [ES08], [AM07]. Here the objective is to determine the conditions under which the handover should be performed, and which radio access network should be selected to obtain better performance. Handover is the process of switching connections among networks; it is either horizontal (between networks with the same access technology), or vertical (between networks with different access technology). Handover makes mobility possible, but also makes a mobile-level topology of cellular/WLAN integrated systems challenging due to user mobility in the study of such systems.

1.2 Objective and scope of the research

The goal of this thesis is to develop an improved mathematical method as an alternative to simulation that, when correctly applied, can be used to improve the radio resource management in heterogeneous wireless networks with an emphasis on cellular/WLAN interworking environment using a traffic engineering approach. Each network node (e.g. cellular BSs, WLAN APs) will be modelled as a queueing model to evaluate the QoS performance such as new call blocking probabilities and handover call dropping probabilities and determine the call admission and resource allocation. Concepts and methods further developed from the hierarchical cellular network can be used to facilitate the analysis of system characteristics and evaluation of interworking performance for heterogeneous wireless networks. I have investigated the key structure characteristics of heterogeneous wireless networks, i.e.

multi-tier overlay structure. Based upon this unique feature, I propose a new network topology scheme to better illustrate the multitier overlay structure and the traffic flow relationship among different cells in the system.

The research will include validation and quantitative analyses of the models. Simulations were used to validate the results obtained from analytic models. Development and validation of queueing model for general heterogeneous wireless networks using this approach are then straightforward.

Most of the previous research on cellular/WLAN integration focuses on developing interworking architectures. The interworking is considered from the perspectives of access selection, security control, mobility management etc. The purposes are to minimize modification to current network standards, reuse existing network infrastructure and reduce implementation complexity at the same time. The models used in these researches are mostly simulation models targeting specific cases of cellular network and WLAN integration. For example, the work I have done in [Song-1] to compare the performance of vertical handover between WCDMA/WLAN and TD-SCDMA/WLAN is based on a simulation model developed using Matlab. However, a highly detailed simulation model implies a large number of parameters and the meticulous implementation of every relevant detail of a specific network increases the complexity of the model and reduces the efficiency and useability, and hence such a model can usually be applied to only very limited situations. Also a simulation model built with specific simulation tools such as OPNET, NS2 and Matlab will inevitably inherit any error that might be contained in these products. Further more, any simulation model will have problems with evaluating rare-event probabilities and with finding steady state values when systems are highly variable as Ward Whitt indicated in [SW96].

This research attempts to develop an analytical model for a general cellular/WLAN integration case to overcome the limits of a simulation model. It has a high level of abstraction focusing on the traffic flows. A good analytic model of a network would be attractive as it would be able to evaluate network performance under a wide range of conditions, and be computed comparatively easily and be likely to be faster than a simulation model It is also essential to the comprehension of the underlying principles thus allowing us to get a better understanding of what is happening. It also has the advantage that a number of numerical optimization techniques for network design can be incorporated [DEE94]. It also will avoid the inherited errors introduced from any simulation development products.

1.3 Research Contributions

The work reported in this thesis is novel. The main contributions are as follows.

- A queueing network analytical model as an alternative approach to the analysis of any possible heterogeneous wireless system with a hierarchical structure with a particular focus on cellular/WLAN interworking. This approach is likely to use much less computing time than a simulation model and provides a better understand of underlying principles of such systems. Such an analytical model is complementary to the various simulation models upon which most of the current research in heterogeneous wireless networks is based.

- A novel logical network topology scheme in the AP (Access Point)/BS (Base Station) level together with a comprehensive node and link traffic analysis method is proposed to overcome the shortcoming of current conventional model and to facilitate the analysis of handover traffic flows in the system. The scheme is especially useful working within the analytical model and proved to be a very powerful tool in its own merits.

- Application of this analytical model to a number of scenarios with various network layouts for both single and multiple types of traffic is discussed in detail.

1.4 Author's Publications

[Song-1] G. Song, L. Cuthbert and J. Schormans: 'Queueing Network Topology for Modelling Cellular/Wireless LAN Interworking Systems', Mobility Management and Quality-of-Service for Heterogeneous Networks, pp 269-285, D. D. Kouvatsos (ed.), River Publishers, March 2009

[Song-2] G. Song, L. Cuthbert and J. Schormans: 'Modelling Cellular/Wireless LAN Integrated Systems with Multi-Rate Traffic Using Queueing Network', WiCom 2008, Dalian, China, October 2008.

[Song-3] G. Song, L. Cuthbert and J. Schormans: 'Open Networks of Loss Systems in the Modelling of Tow-Tier Heterogeneous Hierarchical Overlay Wireless Networks', ChinaCom 2008, Hangzhou, China, August 2008.

[Song-4] G. Song, L. Cuthbert and J. Schormans: 'Network Topology Assisted Handover Analysis for Modelling Cellular/WLAN Integrated Systems' , ICT-MobileSummit 2008, Stockholm, Sweden, June 2008.

[Song-5] G. Song, L. Cuthbert and J. Schormans: 'Queueing Network Topology for Modelling Cellular/Wireless LAN Interworking Systems', HET-NETs'08 - 5th International Workshop Conference on Performance Modelling and Evaluation of Heterogeneous Networks, Karlskrona, Sweden, February 2008.

[Song-6] S. Jin, G. Song and L. Cuthbert: 'Performance Comparison of Vertical Handover between WCDMA/WLAN and TD-SCDMA/WLAN Interworking Systems', AISPC'08 - 2nd Annual IEEE Student Paper Conference, Aalborg, Denmark, February 2008.

1.5 Thesis Outline

The rest of this thesis is organised as follows.

Chapter 2 presents a literature review and background to the subject. First I give the definition of heterogeneous wireless networks and its difference from homogeneous wireless networks. Then I describe the architecture of heterogeneous wireless networks; discuss the advantages and disadvantages of loose coupling and tight coupling. I explain the hierarchical cellular structure that leads to the wider concept of general hierarchical wireless networks. I also explain the importance of vertical mobility management, as vertical handover is a crucial research area of heterogeneous wireless networks.

In Chapter 3, the traffic models used in this project are introduced. Also the birth-death process and multi-class loss system are discussed, as they are the basic theoretical tools for this research.

The network deployment of the analytic system model for a cellular/WLAN interworking system is given in chapter 4 and a new network topology scheme devised to tackle the complex handover traffics is also discussed in this chapter.

In chapter 5 the node traffic and link traffic flows are analysed based on the system setup given in chapter 4. Here the birth-death process is used to analyse a cellular/WLAN interworking system as a typical example of heterogeneous wireless networks.

Multi-rate traffic flow situations are studied in chapter 6. The multi-dimension birth-death process is used to derived the balance equations of the system.

In chapter 7, I set up three scenarios based on the analytic system model given and discussed in Chapter 4 and 5, and give the numerical results and do some analysis on those results. The first scenario is a cellular/WLAN interworking system with symmetric traffic, and this scenario is used to validate the correctness of my model. Then in the second scenario, a cellular/WLAN integrated system with asymmetric traffic with horizontal handover between neighbouring WLANs is considered.

Finally, chapter 8 summarizes the current the research results and contribution and suggests the direction for further work plan and targets.

Chapter 2 LITERATURE REVIEW AND BACKGROUND

2.1 Introduction

Development of new radio access technologies and the increase in user demand for ubiquitous high speed access are driving the deployment of a wide array of wireless networks, ranging from wireless WAN (2G, 3G cellular networks), to wireless MAN (WiMax), wireless LAN (IEEE 802.11 family and HiperLAN) and wireless PAN (Bluetooth, ZigBee). The next evolutionary step for wireless personal communication services will provide an architectural and structural basis that will allow evolving networks to implement free circulation of terminals, personal mobility and network service portability. In the literature, much research addresses the different issues involved in such an interworking system.

In this chapter, I will discuss some of these issues and review key publications. In 2.2, the concept and some major issues in a heterogeneous hierarchical wireless network will be discussed. Queueing network is the basic tool for my modelling work, so an introduction to queueing networks will be given in 2.3. Mobility modelling is discussed in 2.4.

2.2 Heterogeneous Hierarchical Wireless Network

Various wireless network technologies fall into two categories in terms of data rate and coverage: those that provide a low-bandwidth service over a wide geographic area and those that provide a high bandwidth over a limited geographic area. With their complementary characteristics, it is envisioned that Beyond-3G systems will integrate these heterogeneous access networks to offer overlapping coverage to mobile users in order to provide both high bandwidth and good coverage over a range of geographical areas.

This combination of wireless networks fits into a hierarchy of overlapped network, termed wireless overlay network that was introduced by the Bay Area Research Wireless Access Network project [KB96]. Future communications networks are likely to be built upon overlay networks, a unification of several heterogeneous networks of varying coverage and bandwidth into a single network. Figure 2.1 shows an example of wireless overlay network. Lower levels consist of higher bandwidth with limited coverage while higher level would consist of lower bandwidth over a larger geographical area. For example, a mobile terminal in a building can access the wireless LAN in the building and simultaneously be under the coverage of a wide area network like GPRS.

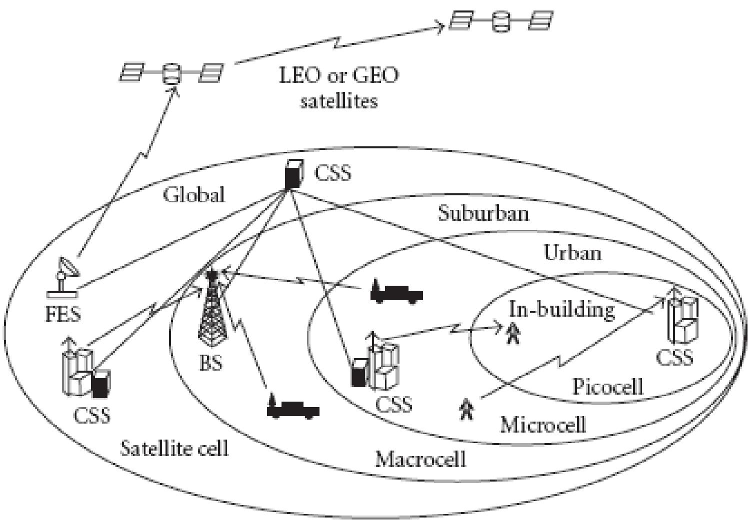

Figure 2.1 Wireless overlay network structure (from [FZJM2006])

Heterogeneous wireless network integration is a very complex issue since it cannot be realized without the cooperation of different network providers and service providers.

In Table 2.1 the idea of a heterogeneous wireless network is further defined from the perspectives of administrative domain and wireless access technology. It can be observed that when the administrative domain and wireless access network are both the same for the component networks then the system would be a homogeneous network. Only when either administrative domain or wireless access technology or both are different, then the system can be called a heterogeneous wireless network. The complexity level to implement such networks is also different for the different configuration. Among them the system with both the different administrative domains and different wireless access technology that can provide general services has the most complicated implementation. The system with the same administrative domain and different wireless technology can provide limited services with easy implementation. The system with different administrative domains and same wireless access technology can provide limited services but with complicated implementation.

Table 2.1 Definition of heterogeneous wireless network

	Same administrative domain	**Different administrative domains**
Same Wireless access technology	Homogeneous	Heterogeneous (Limited services Complicated implementation)
Different Wireless access technology	Heterogeneous (Limited services Easy implementation)	Heterogeneous (General services Most Complicated implementation)

Table 2.2 lists the characteristics of some major wireless access networks that might appear in a heterogeneous wireless environment, including their working frequency, data rate and coverage.

Table 2.2 Characteristics of heterogeneous wireless access systems

Access network type	**Frequency**	**Data rate**	**Coverage**
Bluetooth	2.4 GHz ISM band	Max. 721 kbps	0.1–10 m
IEEE 802.11g	2.4 GHz	54 Mbps	30–150 m
IEEE 802.11b	2.4 GHz	11 Mbps	Up to 100 m
IEEE 802.11a	5 GHz	20 Mbps	50–300 m
HiperLAN2	5 GHz	54 Mbps	150 m max.
IMT2000, UMTS	2 GHz	Max. 2 Mbps	30 m–20 Km
IEEE 802.20	Below 3.5 GHz	Up to 9 Mbps	20 Km
IEEE 802.16	10–66 GHz	Max 70 Mbps	Over 50 Km
GSM, GPRS, HSCSD, EDGE	900,1800,1900 MHz	9.6–384 Kbps	Up to 35 Km
Satellite	Up to 14 GHz	Max 144 Kbps	Several Kilometers
DAB	176–230 MHz; 1452–1467.5 MHz	1.5 Mbps	Up to 100 Km
DVB-T	<860 MHz	5–31 Mbps	Up to 100 Km
DECT/DECT Link	1880–1900 MHz	Up to 2 Mbps	Up to 50 m

The trend of the development of heterogeneous wireless networks is from network-centric multi-service networks to application-centric multi-network service. Instead of user subscribing to just one network provider who provides several services, users now can just subscribe to the services they want and the service provider will deal with the choice of appropriate access networks.

2.2.1 Overall Architecture

The architecture of heterogeneous wireless networks would be a multiple layered hierarchy dubbed as Hierarchical Cellular Structure (HCS), which is discussed in 2.2.5. It will cover all of the proposed operating environments of the mobile user. HCS will support radio environments that range from high capacity picocells, to urban terrestrial micro- and macrocells, to large satellite cells as shown in Figure 2.1.

Due to the potential of satellite links performing as traffic congestion relief and global extensions to terrestrial networks, network capacity will potentially increase – supporting more subscribers and greater traffic volumes without requiring additional radio spectrum for the terrestrial networks.

A mobile user will access the wireless network using a device called a Mobile Terminal (MT). This terminal will use radio channels to communicate to the Base Station (BS) to gain access to the terrestrial networks e.g. PLMN (Public Land Mobile Network), ATM (Asynchronous Transfer Mode) and Internet. In the satellite network, the MT will communicate with Fixed Earth Stations (FES), which govern wireless traffic for satellite terminals, or with the satellite itself. Dual mode terminals will communicate over both the terrestrial and satellite networks.

One of the hottest topic in heterogeneous wireless network architectures is the interworking systems of cellular/WLAN networks, aimed at augmenting the cellular networks with high-rate data services supported by WLANs in hotspots. This is also the technological research focus of this project, so I also give more description in the following part of this chapter. Based on the interdependence between the two access networks, the cellular/WLAN interworking architectures can be classified into two categories which are tight coupling and loose coupling.

2.2.2 Tight coupling architecture

The WLAN is connected to the cellular core network, and appears to the cellular core network as one cellular radio access network. For example, the integration point of WLANs to a GPRS/UMTS core network can be the serving GPRS support node (SGSN) or gateway GPRS support node (GGSN). A user roaming across the two domains is based on the mobility management protocols of the cellular networks, thus enhancing the interdomain mobility management capacity.

The integration architecture proposed in [MMB03, VKV03] are typical tight-coupling examples with the WLAN interfaced at GGSN. The 802.11 gateway in [MMB03] and SGSN emulator SGSN' in [VKV03] meet the UMTS core at the Gn interface if the WLAN is deployed by the UMTS operator or at the Gp interface if by another independent operator. Under the same GGSN, the WLAN and UMTS RAN are different routing areas (RA), while their associated mobiles have IP addresses assigned from the same pool. Then, roaming across the WLAN and UMTS results in Inter-SGSN RA Update without IP address change. Following the UMTS mobility management, the mobile's location is maintained by the home subscriber server (HSS), while the packet data protocol (PDP) context is tracked via an 802.11 gateway or SGSN. Packets that arrive at the GGSN from external networks can then be tunnelled to the mobile.

As proposed in [AKS02, MJ03, SLT02], the tight coupling can also connect the WLAN to SGSN as an alternative cellular RAN via the Iu-ps interface or Gb interface for legacy GPRS network. In [AKS02], an interworking gateway named GPRS interworking function (GIF) is implemented to hide WLAN particularities. In [MJ03], an RNC emulator is used to connect the WLAN at the SGSN, similar to the SGSN emulator SGSN′ in [VKV03]. The UMTS layer-3 procedures can be followed for mobility management and session management. With the WLAN viewed as a typical RA by the SGSN, seamless mobility is achieved by means of Intra-SGSN RA Update instead of inter-SGSN RA Update for the case of interworking at GGSN.

The integration is even tighter by coupling at the RNC level via the Iub or Iur interface. In [NV04], an interworking unit is proposed to handle integration-specific and radio procedures. For interworking at the Iub interface, WLAN-related signalling can be carried via the UMTS interface or over the WLAN. In contrast, the interworking unit working at the Iur interface emulates part of the functionality of a drift RNC associated with a serving RNC. As existing Iur interfaces do not support all control procedures related to call establishment like the Iub interface, the WLAN cannot function independently of the UMTS network.

The preceding tight coupling can reuse the existing cellular infrastructure to a large extent, while the cellular radio is simply replaced with WLAN radio. User roaming across the two domains is mainly based on cellular mobility management, which enhances inter-domain mobility support. Particularly, the cellular infrastructure is mostly reused with the interworking at the RAN level and the handover latency is expected to be minimal.

The advantages of the tight coupling approach are that:

- Seamless service continuation across WLAN and GPRS enabling user to maintain data sessions as they move from WLAN to GPRS/UMTS or vice versa;
- Reuse of GPRS Authentication, Authorization and Accounting (AAA);
- Reuse of GPRS infrastructure (core network resources, subscriber databases, billing systems);
- Access to GPRS core services as such Short Messaging Service (SMS), location-based services, Multimedia Messaging Service (MMS);
- Common provisioning and customer care.

And the disadvantages are:

- Tailored for WLANs owned by cellular operators and can't support third party WLANs;
- Require extensive modifications of WLAN interface beyond existing standards;
- Capacity of cellular wireless networks cannot accommodate the bulky data traffic from WLAN.
- Cannot support WLAN that do not implement GPRS mobility management protocols;
- High cost for connecting a WLAN to an SGSN.

As we can see, the main disadvantage of tight coupling is the high implementation complexity. An interworking unit equipped with a cellular-compatible interface is necessary to expose the WLAN to the cellular core or even the cellular RAN. Moreover, as today's 3G cellular networks are designed to support low-rate data traffic, the 3G core may become a potential bottleneck with the injection of high-rate WLAN traffic. Relatively, the interworking at GGSN may cause less congestion since a large part of the data traffic bypasses the cellular core. Nonetheless, the network elements of the cellular core or RAN should be upgraded to support the extra traffic from WLANs. Furthermore, the cellular protocols tailored for highly mobile users in hostile outdoor environments may not operate properly for WLANs [RP00]. Thus, radio resource management (RRM) and radio resource control (RRC) need to be modified and adapt to the involved networks. With tight coupling, it is possible to apply joint resource allocation to optimize overall system capacity. A best radio interface available can be selected with a proper decision algorithm. Therefore, the tight-coupling architecture with the above characteristics is ideal to integrate WLANs deployed by cellular operators.

2.2.3 Loose coupling architecture

For the loose-coupling approach, the two networks are integrated beyond the core networks and usually through an external IP network such as the Internet. Among this category, typical examples include the second architecture proposed in [MMB03] and that in [AKS02], the peer network architecture in [VKV03], the mobile IP approach in [SLT02], the gateway approach in [JCC05], and the operator WLAN system (OWLAN) in [JAL01].

It is well recognized that wireless networks are evolving toward being all-IP, as shown in the specification [3GPP04] for the 3G cellular network cdma2000. Many IP-based technologies are introduced in the 3G core network, e.g. Mobile IP [CP02] for mobility management and authentication, authorization and accounting (AAA) [CL00] framework for user access control. The 3G core networks evolve to function more like an IP backbone. For the WLAN as a wireless extension of wired Ethernet, since only the physical layer and link layer are specified, it is a natural choice to adopt popular IP-based protocols for higher layers. The loose-coupling architecture usually employs the pervasive IP technology to glue together the cellular network and WLANs, and follows the de facto standards of the Internet community such as Mobile IP and AAA framework. As a result, within the two networks, different mechanisms can be implemented independently to handle user mobility, authentication, etc. Seamless roaming across the two networks can be achieved with the help of Mobile IP. Also, with the flexible AAA frameworks, 3G-specific authentication mechanisms can be reused, while independent WLAN service providers can implement their preferred authuentication methods such as the popular standards in the Internet community. Although imposing minimal modification to the WLAN, the loose coupling approach requires the cellular network to be augmented with extra functionalities such as Mobile IP and AAA support.

On the other hand, the loose coupling approach is relatively inefficient because of a long signalling path, redundant processing in the two networks, and a large number of network elements involved in management operations. For instance, because the mobility signalling has to traverse a long path across two separated domains, a relatively high handover latency is induced. To overcome the inefficiency, it is necessary to apply extra techniques such as cross-layer control and context management. Mobile IP enhancement mechanisms such as regional registration and dynamic home agent assignment can be applied to reduce handover latency. The signalling procedure can also be simplified by coupling the authentication/authorization procedure with mobility management.

In fact, the future wireless network is expected to be a converged network, in which a common IP-based core network is shared by a variety of access networks [KS05]. The access technology-specific functions only propagate from the gateway to the shared core network. As such, the access heterogeneity terminates within the access network and homogeneous management is provided for mobility, security, QoS, etc. Although heterogeneous systems in the future converged network are expected to share a common core network as in the tight coupling, the shared core may not necessarily be the cellular core. Similar to the loose coupling, the common core network can be a separate independent deployment and flexible implementation, the loose-coupling architecture has been preferably adopted in many research work to address different interworking problems. Nonetheless, the tight coupling with enhanced performance tends to be the next logical step toward seamless cellular/WLAN interworking.

The gateway directly connects the WLANs to the Internet backbone, and there is no direct link between the WLANs and the cellular core network.

The advantages of the loose coupling are:

- Impose minimal changes in both WLAN and cellular data network;

- Allow independent deployment and traffic engineering of WLAN and 3G networks.

Disadvantages:

- Mandate the provision of new network equipment such as AAA servers for interconnecting with WLANs;
- Seamless handover is not possible due to the typical high latency associated with mobile IP registration;
- Billing more complicated.

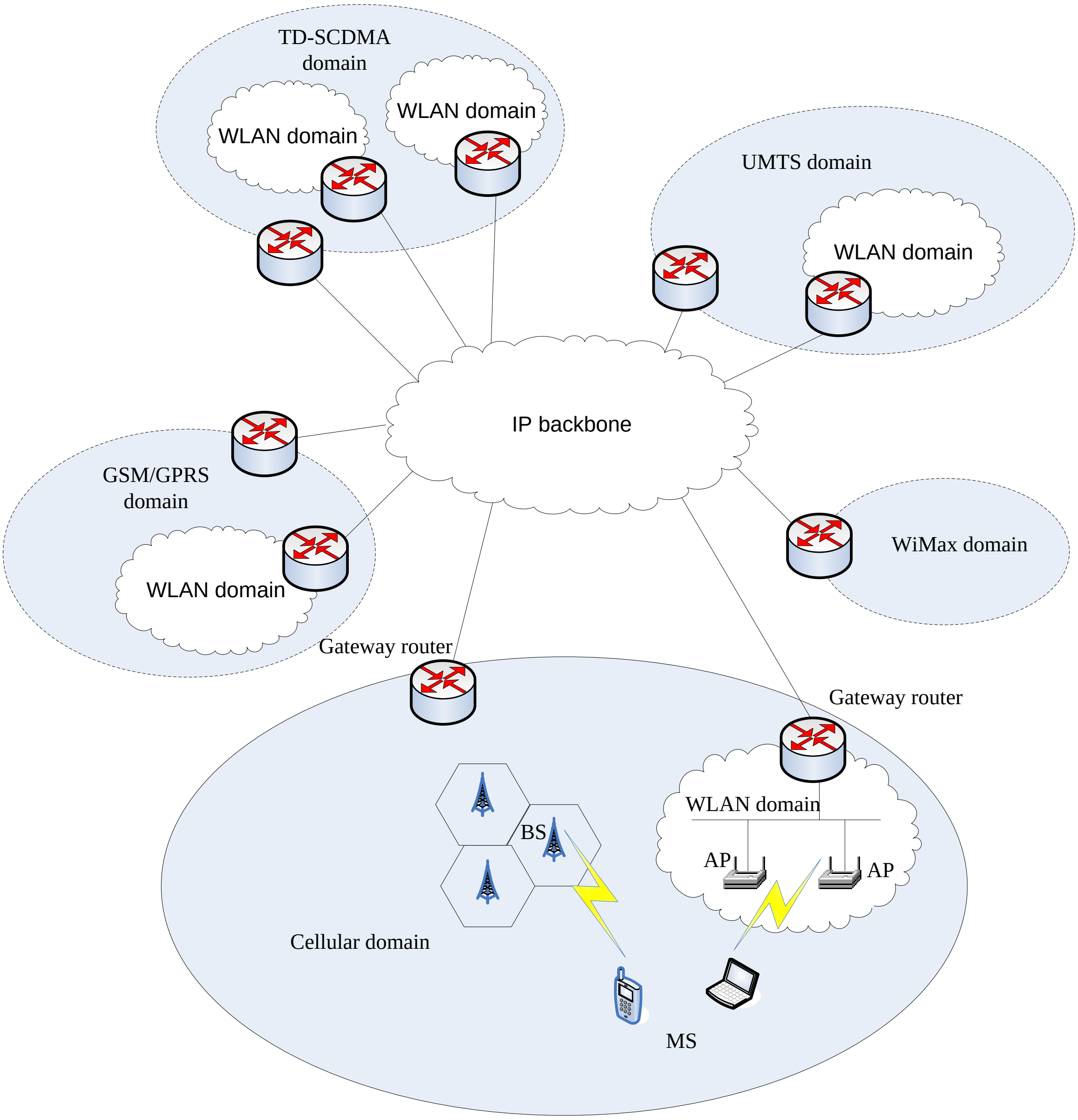

Figure 2.2 Loosely coupled cellular/WLAN interworking architecture

On the other hand, to interconnect heterogeneous IP-based wireless access networks with the Internet backbone in 4G networks, it is well recognized that an all-IP DiffServ platform is the most promising architecture to provision broadband seamless global access for the following reasons:

- Based on a limited number of services classes, DiffServ is a scalable mechanism as no per-flow processing is needed in the core network

- The DiffServ platform adopts a domain-based architecture, where each domain can freely and independently choose its own system mechanisms as long as its service level agreements (SLAs) with neighbouring domains are satisfied. Such a domain-based architecture allows the flexibility and convenience to deploy each domain independently, and to develop, modify, or exchange the techniques in a domain without a significant impact on the overall system.

- The newly emerged IEEE 802.11e draft for WLANs aims at provisioning Quality of Service (QoS) in a relative sense, which is similar to and can be mapped smoothly to the relative QoS in DiffServ.

- A fast handover procedure is required for seamless roaming in and among wireless access networks. The popular solution for fast handover is to use Mobile IP for interdomain (macro-) mobility and to use micromobility protocols for intradomain mobility. Micromobility protocols can be seamlessly incorporated in the domain-based DiffServ platform.

The level of abstraction of my analytical model is above tight/loose coupling. The principle would work with any type of coupling as all that is assumed is the ability to handover.

2.2.4 Heterogeneous Wireless Network Characteristics

The heterogeneity in the physical, medium access and link control layers leads to the different radio resource management solutions. There is a centralized architecture in cellular networks, in which the BS has the ability to provide QoS guarantee to MSs via properly scheduling their access to the wireless channel, taking advantage of the information available in the BS and collected from MSs. Furthermore, the schedulers located in different BSs can also coordinate with each other to improve overall system performance.

On the other hand, in the current major WLAN standard IEEE 802.11b, two channel access functions are defined: the mandatory distributed coordination function (DCF) in a centrally controlled manner. The most popularly commercialized DCF is based on carrier sense multiple access with collision avoidance (CSMA/CA) and binary exponential backoff, which cannot guarantee user QoS requirements. The IEEE 802.11e standard has been released in 2005. It provides a set of QoS traffic capabilities based on a new function called HCF (Hybrid Coordination Function), which provides an enhanced version of both the DCF and PCF, now called EDCA (Enhanced Distributed Channel Access) and HCCA (HCF Controlled Channel Access). This new version includes the required functions to differentiate traffic streams and thus, provide different QoS levels.

Except for the heterogeneity in the access networks, a hierarchical structure is another major feature for the next generation wireless networks. A hierarchical structure is not a new concept in the wireless world. One trend in cellular networks is to adopt the hierarchical cellular structure that is already mentioned in 2.1, and it has been widely studied. The basic idea is to use the overlaid cells with different sizes to optimize overall resource allocation taking the different level of user mobility into consideration.

2.2.5 Hierarchical Cellular Network

With the rapid growth in the number of subscribers, and more services placing extra demands on system capacity, one method to ease the pressure is to shrink the cell size in order to accommodate more mobile users and traffic in a given area. The small-cell system has the advantages of greater spectral reuse and larger capacity than those of large-cell systems, and also allows the use of low power hand-held devices. However, small-cell systems have the disadvantages of increased mutual interference and cell-boundary crossings (i.e. mobility-driven handover) over those of large-cell systems. With inadequate resources provisioned, increased handover rate can lead to high forced call termination probability.

In order to achieve and maintain high network performance, one network design approach is to use a hierarchical cellular structure. In this structure, cells of different sizes are organized into different layers to provide high coverage and capacity over a given service area. This structure can effectively reduce the number of handovers in the wireless system, thus significantly improving the overall system capacity

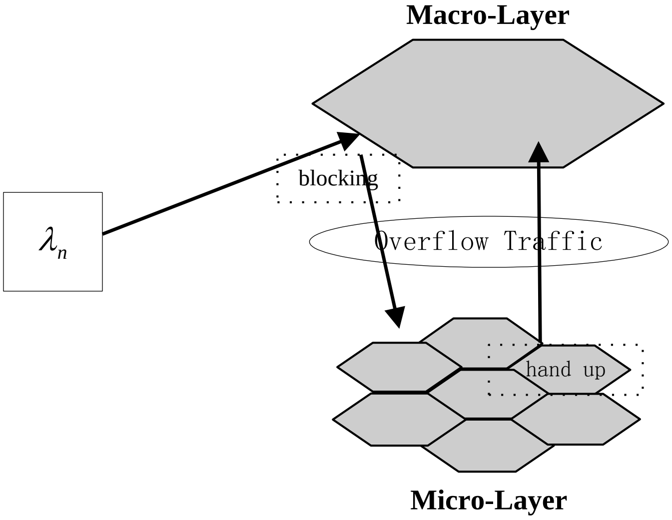

Figure 2.3 Traffic for two tier hierarchical cellular network

There are a number of different approaches proposed for handling calls in HCS. Rapport and hu in [RSHL94] presented an approach where a new call or a handover call will be directed to the appropriate layer based on its previous speed. In Lagrange and Godlewski's[LXGP96], only handover overflow from the lower layer to the higher layer is allowed. Lee and Cho in [LDCD00] proposed that mobile subscribers travelling in the lower layer may borrow channels from a pool of channels reserved for handover calls at the higher layer. Chung and Lee [CSLJ02] presented a mobility-dependent connection admission control scheme, which was analysed assuming the interrupted Poisson process (IPP) under stationary and non-stationary conditions.

2.2.6 Hierarchical Cellular/WLAN Overlay Architecture

By replacing the micro-cells in a hierarchical cellular network with WLANs, we can utilize many useful methods developed in hierarchical cellular network research.

The cellular networks have widely entrenched infrastructure, which provides almost ubiquitous connectivity and supports user mobility levels from fast highway vehicles to stationary users in an indoor environment. In contrast, WLANs are usually deployed disjointly in hotspot local areas. Thus, the cellular/WLAN interworking results in an overlay structure similar in some way to hierarchical cellular structure. Both cellular access and WLAN access are available to mobile within WLAN-covered areas. The incoming traffic load should be properly shared between the overlay cell and WLAN for QoS enhancement, congestion relief, cost reduction, etc.

Though here I extensively reviewed the idea of a cellular/WLAN interworking system, the method I developed in my research will actually work for any multi-layer hierarchical overlay wireless network. Cellular/WLAN interworking is just used for the most part of this thesis as one example of a two-tier heterogeneous wireless network. It can be easily applied to any other heterogeneous wireless network with the similar multi-tier hierarchical structure.

2.3 Queueing Networks

Queueing theory has a long history of application in research in telecommunication systems starting from Agner. K. Erlang who gave birth to queueing theory and set the foundation stone of teletraffic engineering in his two papers [AKE09, AKE17] on the calculation of performance probabilities in telephony published in the early 20th century.

James R. Jackson first developed the theory of queueing networks in his study of a special type of network of queues [JRJ63] named after him as Jackson Networks. A queueing network is a network of queues where the departures from one queue enter the next queue. It can be classified into two categories: open queueing networks and closed queueing networks. Open queueing networks have an external input and an external final destination. Closed queueing networks are completely self-contained and the customers circulate continually never leaving the network. As an important branch of queueing theory, queue networks have been used extensively in the modelling and analysis of both wired networks and wireless networks for the traffic level study. The heterogeneous wireless networks I will study can be modelled as a open queueing network as it can be found out later such systems have external input and outgoing traffics.

Queueing networks can be described as a group of nodes where each node represents a service facility of some kind. In the most general case, customers may arrive from outside the system at any node and may depart from the system from any node. Thus customers may enter the system at some node, traverse from node to node in the system, and depart from some node, not all customers necessarily entering and leaving at the same nodes, or take the same path once having entered the system. Customers may return to nodes previously visited, skip some nodes entirely, and even choose to remain in the system forever.

Analytic evaluation of a queueing network involves using an algorithm to solve efficiently a set of equations that describe the network of queues and its parameters. In this research I focus on traffic blocking through the measure of call blocking probability.[1]

2.4 Mobility Modelling for My Analysis

Mobility is a major characteristic of many wireless network systems. It allows user to benefit from network services in all of the service area and to communicate while they move across the network. Most of all, it results in the occurrences of handover. Mobility models as a way to represent the custom mobility patterns play an important role in examining different issues in a wireless system such as handover, offered traffic, dimensioning of signalling network, user location updating, registration, paging multilayer network management etc. In my research, the mobility model is mainly used for handover analysis.

2.4.1 Handover Rate Related Mobility Model for Cellular Network

An important way to evaluate mobility is to use the handover traffic rate as a percentage of the new traffic. This model doesn't require complex mathematical calculations and it can be used to represent efficiently mobility in a cellular environment.

We denote the duration of an unencumbered call by the random variable τ and its mean by $\tilde{\tau}$. We assume that τ follows an exponential distribution with parameter $\mu = \frac{1}{\tilde{\tau}}$. A call can comprise successive sessions τ_1 , τ_2 , $\tau_3 \ldots$ in cells traversed by a mobile terminal (Figure 2.4 below). The residual time of a mobile within a cell is denoted τ_h, and we assume that it is also exponentially distributed and its mean is $\tilde{\tau}_h$. If the cell crossover rate is n, then we can estimate $\tilde{\tau}_h$ by the

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[1] This should not be confused with switch internal blocking probabilities.

form $\tilde{\tau}_h = \frac{1}{n}$. From $\tilde{\tau}$ and $\tilde{\tau}_h$ we can estimate the channel occupancy time τ_c, which is either the time spent in a cell before crossing the cell boundaries if the call continues, or the time until the channel is released (Figure 4.1) in other words $\tau_c = \min\{\tau, \tau_h\}$.

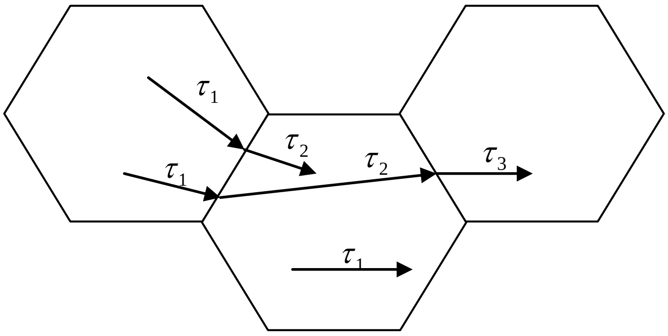


Figure 2.4 Residing time and channel occupancy time

As it is already mentioned τ and τ_h are exponentially distributed. In [FHGL95, DBRG92] it is shown that minimum of the two exponentially distributed random variables it is also exponentially distributed with parameter $\mu_c = \mu + n$. Therefore the mean channel occupancy time for a new or handover call is given by

$$\tau_c = \frac{1}{\mu_c} = \frac{1}{\mu + n} \tag{2.1}$$

The probability of handover is given by

$$P_h = P\{\tau > \tau_h\} = \frac{n}{\mu + n} \tag{2.2}$$

We define the mean number of handovers per call with the parameter ν. This parameter, in general, is the handover attempt rate during the unencumbered call duration. In [SN93] it is shown that for a general distribution for cell residing time this parameter is given by the ratio of the mean call holding time to the mean cell residing time, that is

$$\nu = \frac{\tilde{\tau}}{\tilde{\tau}_h} = \frac{\mu}{n} \tag{2.3}$$

From (2.1) and (2.3) the mean channel occupancy time in a cell τ_c, is given from the following relation

$$\tilde{\tau}_c = \frac{1}{1+\nu}\tilde{\tau} \tag{2.4}$$

Note that the total offered load to a cell is dependent on the handover traffic, which in turn depends on the total offered traffic to the cell. Using the equilibrium property we can write

$$\lambda_h = P_h\left[(1-P_b)\lambda_l + (1-P_h)\lambda_h\right] \tag{2.5}$$

and subsequently solve for λ_h

$$\lambda_h = \frac{P_h(1-P_b)}{1-P_h(1-P_h)}\lambda_l \tag{2.6}$$

where P_b is the call blocking probability and P_h is the handover dropping probability.

In (2.6) if we consider small values of P_b and P_h, and by using (2.2), (2.3) the λ_h is given by

$$\lambda_h \cong \frac{n}{\mu}\lambda_l = \nu\lambda_l \tag{2.7}$$

From (2.7) we can observe that the handover rate is given as a percentage of the total new traffic rate in a cell. It is also depend on the mean number of handover per call.

2.4.2 *Mobility Model for Cellular/WLAN Interworking*

For a cellular and WLAN overlaid wireless network, the mobility characteristics of mobile stations have some distinctive difference from either 3G or WLAN network alone.

WLANs are basically deployed indoor where user mobility is low. While in cellular coverage, user mobility is much higher. But if we consider a cellular and WLAN overlaid network, then the mobility behaviour within WLAN becomes more complicated. The residence time has some heavy-tailed feature, i.e. most of the users stay within a WLAN for a relative short period, while a small fraction of users has an extremely long residence time. As performance analysis is extremely difficult with heavy-tailed distributions, it is proposed in [WS07A] to use a two-stage hyper-exponential distribution to approximate the residence time in WLAN, which is simple and also well captures the high variability. If we define the time period a user spends within WLAN as T_r^W , then the probability density function (PDF) of T_r^W with mean $\frac{1}{\eta^w}$ is given by

$$f_{T_r^w}(t)=\frac{a}{a+1}\cdot\frac{1}{\frac{1}{a}\cdot\frac{1}{\eta^w}}e^{-a\eta^w t}+\frac{1}{a+1}\cdot\frac{1}{a\cdot\frac{1}{\eta^w}}e^{-\frac{\eta^w}{a}t}\qquad a\geq 1,\qquad t\geq 0 \tag{2.1}$$

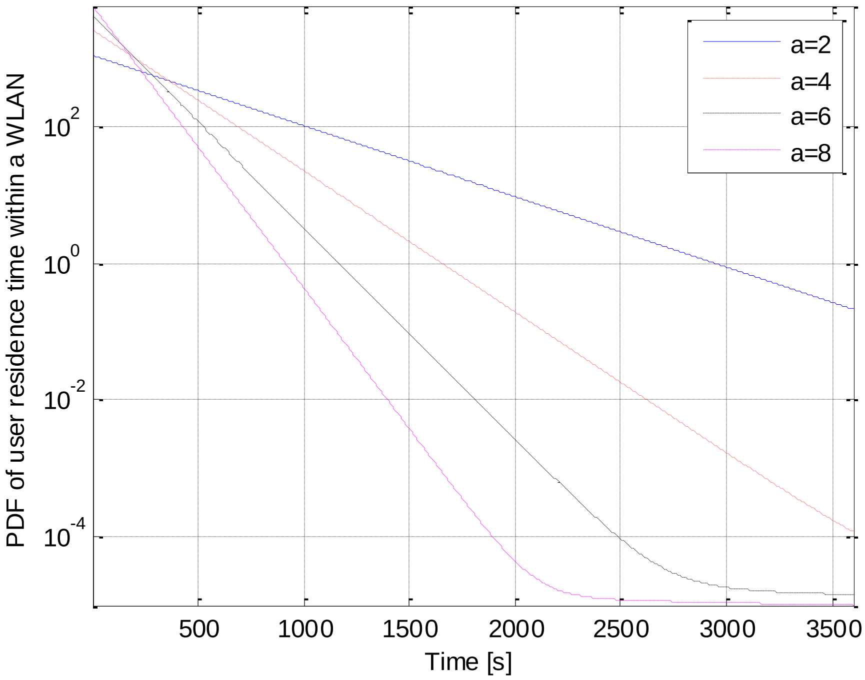


Figure 2.5 PDF of user residence time within WLAN

We can see that a large fraction $\frac{a}{a+1}$ of the mobile stations stay within the coverage of WLAN for a mean time $\frac{1}{a}\cdot\frac{1}{\eta^{w}}$, while the other small fraction $\frac{1}{a+1}$ of the mobile stations have a mean residence time of $a\cdot\frac{1}{\eta^{w}}$. Here a can be defined as a mobility variability parameter, with its increasing it results in T_{r}^{W} with a higher variability.

I used this mobility model in simulation to test the handover probability of users within a WLAN. The simulation time is 10 minutes. The arrival rate λ of user call is 0.1, with mean duration time $\frac{1}{\mu}$ as 180 seconds as the parameters used by Wei in [WSWZ07]. If user's residence time is longer than the call duration time which means while the user is making this call, he keeps staying in the coverage of WLAN AP, then no handover will occur, otherwise a handover will happen. The results are given in the Figure 2.6 with mobility parameter a changing from 1 to 8. Box and whisker diagram is used here with the smallest observation, lower quartile, median, upper quartile, and largest observation values all in one graph. The box has lines at the lower quartile, median, and upper quartile values. Whiskers extend from each end of the box to the adjacent values in the data—by default, the most extreme values within 1.5 times the interquartile range from the ends of the box. Outliers are data with values beyond the ends of the whiskers. Outliers are displayed with a red + sign.

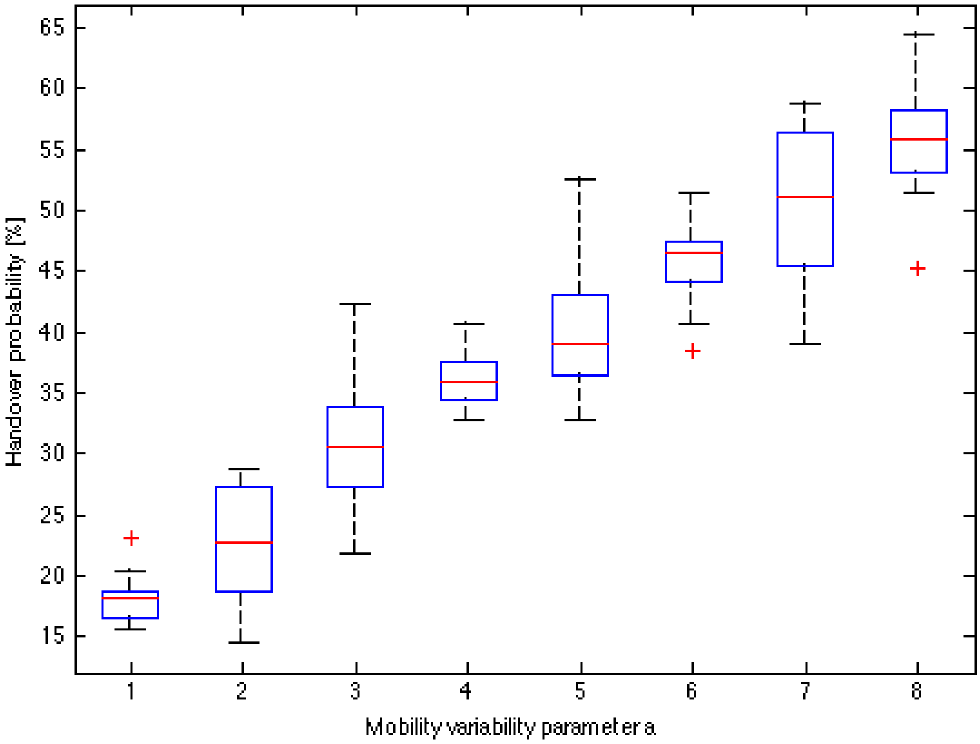


Figure 2.6 Relationship between handover probability and mobility variability parameter

It can be observed that an increase of the number of users with high mobility will increase dramatically which leads to the rise of handover probability. This issue of the influence of the mobility upon the handover behaviour will be considered in my cellular/WLAN interworking system model.

2.5 Motivations

Previously, research on heterogeneous hierarchical wireless network integration focuses on relatively high-level issues such as integration architecture as introduced in 2.1.1. Integration is considered from the perspective of access control and security, mobility management, billing, etc. The objectives are to minimize modification to current network standards, reuse existing network infrastructure, and reduce implementation complexity at the same time. In particular, vertical handover management has attracted substantial research attention. The handover between wireless networks of different access technologies is referred to as vertical handover, in contrast to horizontal handover within a homogeneous wireless network, e.g., between base stations of cellular networks or access point of WLANs. Many vertical handover algorithms are proposed to achieve seamless and fast handover between the cell and the WLAN [QZWZ03, CGW04].

However, there is still not much research effort devoted to resource allocation for integrated heterogeneous wireless networks. This research area is actually very important as the integration only becomes really meaningful if the overall resources are efficiently utilized. Many new challenges need to be addressed as given in chapter 2 to chapter 5. In particular, with an overlay structure, the incoming traffic load can be properly shared between the integrated systems. Due to the heterogeneous underlying network support, the call assignment strategy can significantly affect user QoS experience and resource utilization of the integrated network. Moreover, the desired load sharing can be enhanced with call reassignment, i.e., ongoing calls are dynamically transferred between different networks via vertical handover.

For the interworking between a cellular network and WLANs as an example, there is a two-tier overlaying structure [WS07], similar to a two-tier hierarchical cellular structure, in which small-size microcells overlay with large macrocells. Quite a lot of research has been done on hierarchical cellular networks using queueing theory in modelling, such as in [XLAF06, SPLH94]. By replacing the microcells with WLANs, many methods used in hierarchical cellular network can actually be applied in a cellular/WLAN interworking system or further into any hierarchical heterogeneous wireless network.

Due to the difficulties in mathematically modelling complicated traffic features (like handover) of a hierarchical heterogeneous wireless network, the majority of research in the literature has been performed using simulation. For example, the work I have done in [Song-6] to compare the performance of vertical handover between WCDMA/WLAN and TD-SCDMA/WLAN is based on a simulation model developed using Matlab. However, meticulous implementation of every detail of a specific network increases the complexity of the model and reduces the efficiency and hence such a model can usually be applied to only very limited situations. Thus an analytic model of a network would be attractive as it would be able to evaluate network performance under a wide range of conditions, and to be computed comparatively easily. It is also essential to the understanding of the underlying principles and it has the advantage that it can incorporate numerical optimization techniques for network design [DE94].

Network topology analysis is widely used in the study of wired networks. It is a powerful tool in the analysis of some wireless mobile networks such as MANET (mobile ad-hoc network), in which mobile customers are modelled as nodes connected by wireless links, so forming a physical wireless topology. Such wireless topologies are defined as *mobile-level topologies* in this thesis. However compared to its usage in wired networks, the application of network topology analysis in wireless networks is still very limited. This is largely due to the mobility of the mobile terminals, so the physical network topology is not stable, but evolving all the time. Network topology is even more rarely used in the study of cellular wireless networks or infrastructure WLANs because the physical mobile-level network topology of each cell in cellular network or Basic Service Set (BSS) in WLAN would be just a simple star structure.

Hence, research on an analytic model of a hierarchical heterogeneous wireless network, especially a cellular/WLAN interworking, is still a hot topic. Wei first introduced the method for hierarchical cellular networks into a cellular/WLAN interworking system and analyzed in [WS06, WS07], via a rigid cell cluster structure with only one WLAN in each overlaid cellular cell. She models the cell/WLAN as a multi-class loss system, then use an approximation method to obtain the steady-state probabilities. Stevens-Navarro and Wong in [ESN07] further developed an analytic model using birth-death process analysis. The model he proposed loosens the constraint on the number of WLANs in each cellular cell.

In my research, I introduce a new network topology scheme to facilitate the analysis of handover traffic flow in a cellular/WLAN integrated system, thus extending the modelling method of Stevens-Navarro and Wong and modelling a cellular/WLAN interworking system as an open network of loss systems with the help of this logical wireless network topology. A simple integrated system with three cellular cells and three WLANs is evaluated based on this analytic model. Numerical results are given and discussed.

I focus my model on the circuit switch traffic, but it can be also applied to the packet switch traffic such as VoIP as the traffic model is on flow-level.

2.6 Summary

In this chapter I gave the literature review and background information. I discussed the definition, structure and architecture of heterogeneous hierarchical wireless networks in 2.1 and 2.2. I introduced the development of queueing network theory and its usage in the modelling of communication networks. I also discussed the mobility model in 2.4. Finally I gave the motivations for my research in 2.5.

Chapter 3 SINGLE CELL LOSS SYSTEM MODELLING

In queueing theory loss systems are used as models for connection-oriented networks, where the sharing of the available resources is based on reservations made in the connection establishment stage. Calls arrive randomly according to some specified stochastic process. Which specific resources an arriving call needs depends on the class of the call. If these resources are not available at the arrival time, the call is blocked and lost. Otherwise the required resources are reserved and the connection is established.

The analysis of loss models is nowadays relatively mature, and it is used in my system for modelling the celluar/WLAN interworking network discussed in Chapter 6, so I will explain how loss system modelling works in this chapter.

3.1 Introduction

Loss systems may be the simplest but most widely used and well studied teletraffic models. These can be catalogued as a class of resource allocation models that have proved useful in the study and design of communication networks, including cellular mobile networks, integrated services digital networks, database structures and multiprocessor architectures. There are already monographs on loss systems such as [KWR97]. The basic performance measure of loss systems is blocking probability. Although many of these systems have explicit formulae for blocking probabilities, it often requires too much processor time to perform the calculations, making it necessary to use approximation techniques. Among these approximation techniques, the Erlang fixed point approximation is the most famous and efficient one [KF91]. It is closely related to the standard voice traffic model.

3.2 Voice Traffic

The conventional class is characterized by a two-way conventional communication pattern. A typical example is voice telephony, which has been extensively studied and widely deployed. Generally voice traffic can be represented by a two-state on/off model, a voice user is alternatively in talk spurt and in silence.

3.3 *Single class traffic—Erlang loss model*

3.3.1 *Erlang's analytic model*

The most rudimentary loss system model is the Erlang loss model. Proposed by A. K. Erlang, circa 1917, the model is first to model a single line in a telephone network with a fixed carrying capacity. It has an infinite number of independent customers $k = \infty$. The random variable describing the IID (interarrival times are independent and identically-distributed random variable) follows the exponential distribution with mean $1/\lambda$ (i.e., customers arrive according to Poisson process with intensity λ). There are a finite number of servers $n < \infty$, and no waiting places, so if the system is full with all n servers occupied, when another customer arrives, it is not served but lost. The service time of each customer is also an independent and identically-distributed (IID) random variable following the expnontial distribution with mean $1/\mu$. The traffic intensity is defined as $\rho = \lambda/\mu$. Using Kendall's notation, this Erlang model is actually an M/M/n/n queue.

Let $X(t)$ denote the number of customers in the system at time t. Assume that $X(t) = i$ at some time t, and consider what happens during a short time interval $(t, t+h]$. We can get that with a probability of $\lambda h + o(h)$, a new customer arrives. It is represented in the state transition diagram as state transition $i \to i+1$; and with a probability of $i\mu h + o(h)$, a customer leaves the system, so the state transition is $i \to i+1$. The Process $X(t)$ is clearly a Markov process with state transition diagram shown in Figure 3.1.

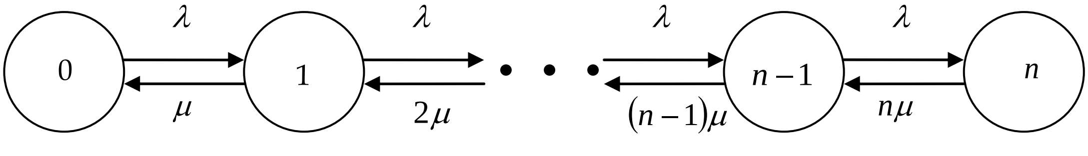


Figure 3.1 State transition diagram for M/M/n/n queue

We notice that process $X(t)$ is an irreducible birth-death process with a finite state space $S = \{0,1,2,\cdots,n\}$

The local balance equations (LBE) are:

$$\pi_i \lambda = \pi_{i+1}(i+1)\mu \tag{3.1}$$

$$\Rightarrow \pi_{i+1} = \frac{\lambda}{(i+1)\mu}\pi_i = \frac{\rho}{i+1}\pi_i \tag{3.2}$$

$$\Rightarrow \pi_i = \frac{\rho^i}{i!}\pi_0, \qquad i = 0,1,\ldots,n \tag{3.3}$$

With the normalizing condition, we have

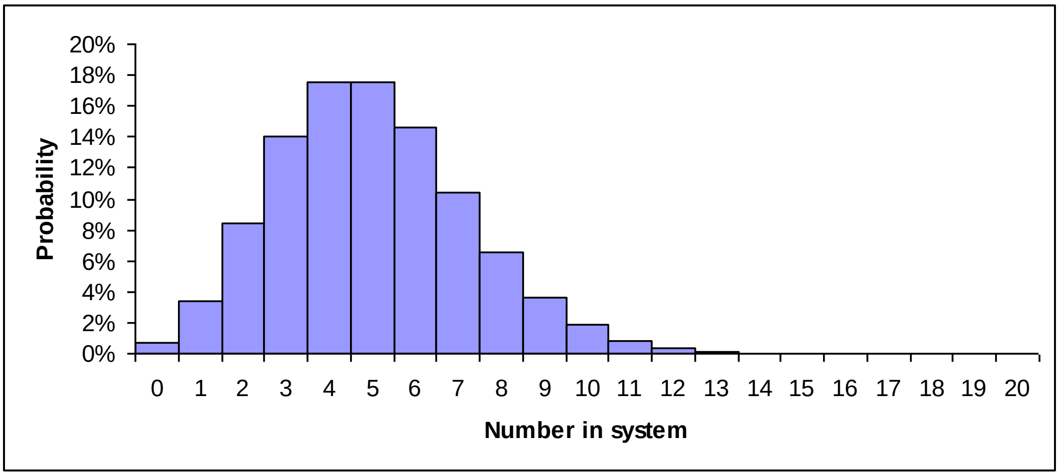
$$\sum_{i=0}^{n}\pi_i = \pi_0 \sum_{i=0}^{n}\frac{\rho^i}{i!} = 1 \tag{3.4}$$

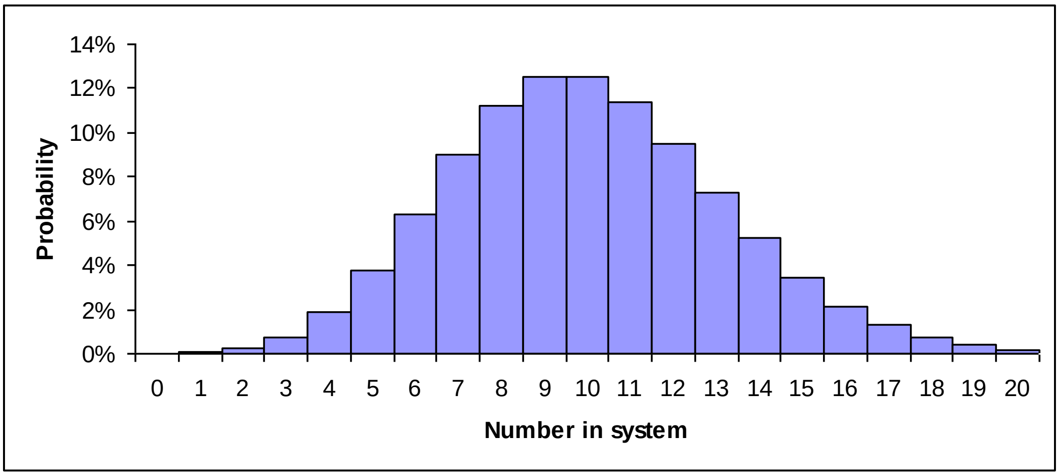
$$\Rightarrow \pi_0 = \left(\sum_{i=0}^{n}\frac{\rho^i}{i!}\right)^{-1} \tag{3.5}$$

Thus, the steady state distribution (equilibrium distribution) is a truncated Poisson distribution

$$P\{X = i\} = \pi_i = \frac{\frac{\rho^i}{i!}}{\sum_{j=0}^{n}\frac{\rho^j}{j!}}, \qquad i = 0,1,\ldots,n \tag{3.6}$$

This result is insensitive with respect to the service time distribution, i.e., it is valid for any service time distribution with mean $1/\mu$. So instead of M/M/n/n model, this is also applicable to the more general M/G/n/n model.





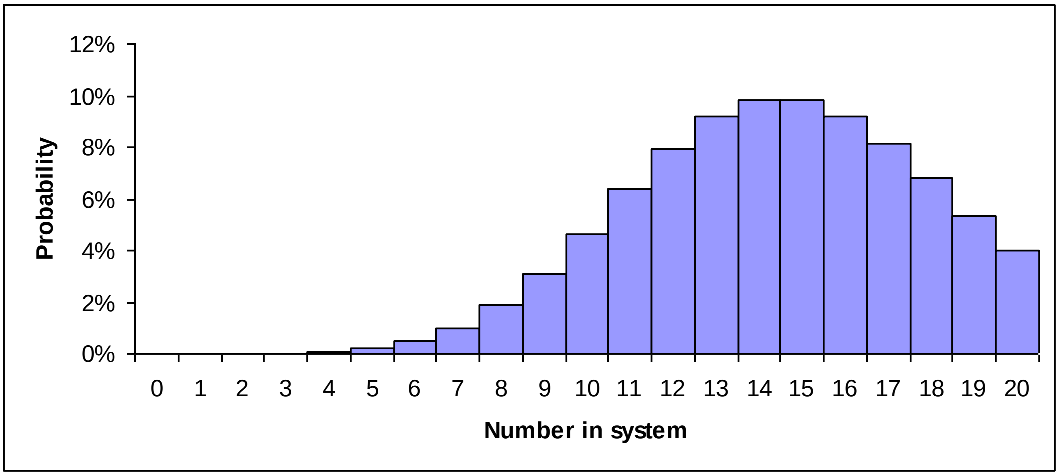


Figure 3.2 Steady state probability for M/M/c/c loss system, system capacity=20, from top to bottom ρ =5; ρ =10; ρ =15;

The time blocking probability B_i is the probability that all n servers are occupied at an arbitrary time, i.e., the fraction of time that all n servers are occupied. For a stationary Markov process, this equals the probability π_n of the equilibrium distribution π. Thus we have

$$B_t := P\{X = n\} = \pi_n = \frac{\frac{\rho^i}{i!}}{\sum_{j=0}^{n} \frac{\rho^j}{j!}} \tag{3.7}$$

The call blocking B_c is the probability that an arriving customer finds all n servers occupied, i.e., the fraction of arriving customers that are lost. However, due to Poisson arrivals and the PASTA property, the probability that an arriving customer finds all n servers occupied equals the probability that all n servers are occupied at an arbitrary time. In other words, call blocking B_c equals time blocking B_i:

$$B_c = B_t = \frac{\frac{\rho^i}{i!}}{\sum_{j=0}^{n} \frac{\rho^j}{j!}} \tag{3.8}$$

This is the famous Erlang-B blocking formula. A validation of the simulation of voice traffic with Erlang-B model can be found in Appendix A.

3.4 Multi-class traffic - Erlang Multi-rate Loss Model

The Erlang multi-rate Loss Model is also a classic model for the system where more than one type of traffic class exists. Because in my next step of research, a multi-service traffic load will be considered in my cellular/WLAN interworking model to take a further good advantage of the complementary strength of the two networks. For example, benefiting from the centralized infrastructure, cellular networks can effectively serve real-time traffic with stringent QoS requirements. On the other hand, WLANs can be a good choice for elastic data services, which may experience traffic asymmetry at the uplink and downlink. The contention-based access of WLANs enables a virtually time division duplex (TDD) mode to efficiently handle the load asymmetry and flexibly adapt to traffic elasticity. So the service type is an important factor in resource allocation for cellular/WLAN interworking. But multi-class traffic would be much more complex to analyze than single-class traffic. Let us just take a two traffic classes as an example to facilitate my analysis.

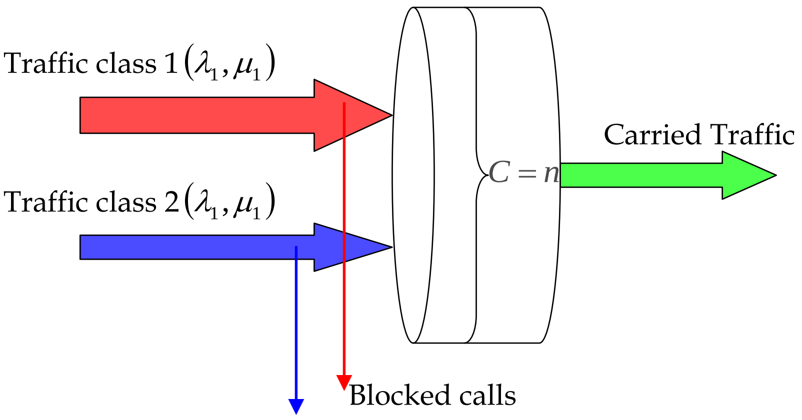


Figure 3.3 Multi-class teletraffic model

I consider a group of n trunks (channels, slots), which is offered two independent traffic streams: (λ_1, μ_1) and (λ_2, μ_2). The offered traffic becomes $\rho_1 = \lambda_1 / \mu_1$ and $\rho_2 = \lambda_2 / \mu_2$ respectively. Let (i, j) denote the state of the system, i.e. i is the number of active calls from stream 1 and j is the number of calls from stream 2. We have the following restrictions.

$$0 \le i \le n \tag{3.9}$$

$$0 \le j \le n \tag{3.10}$$

$$0 \le i + j \le n \tag{3.11}$$

The state transition diagram is show in Figure 3.9. Under the assumption of statistical equilibrium the state probabilities are obtained by solving the global balance equations for each node (node equations), in total $(n+1)(n+2)/2$ equations.

From this diagram, we can find that it corresponds to a reversible Markov process, and the solution has a product form. We can easily show that the global balance equations are satisfied by the following state probabilities which can be written in product form:

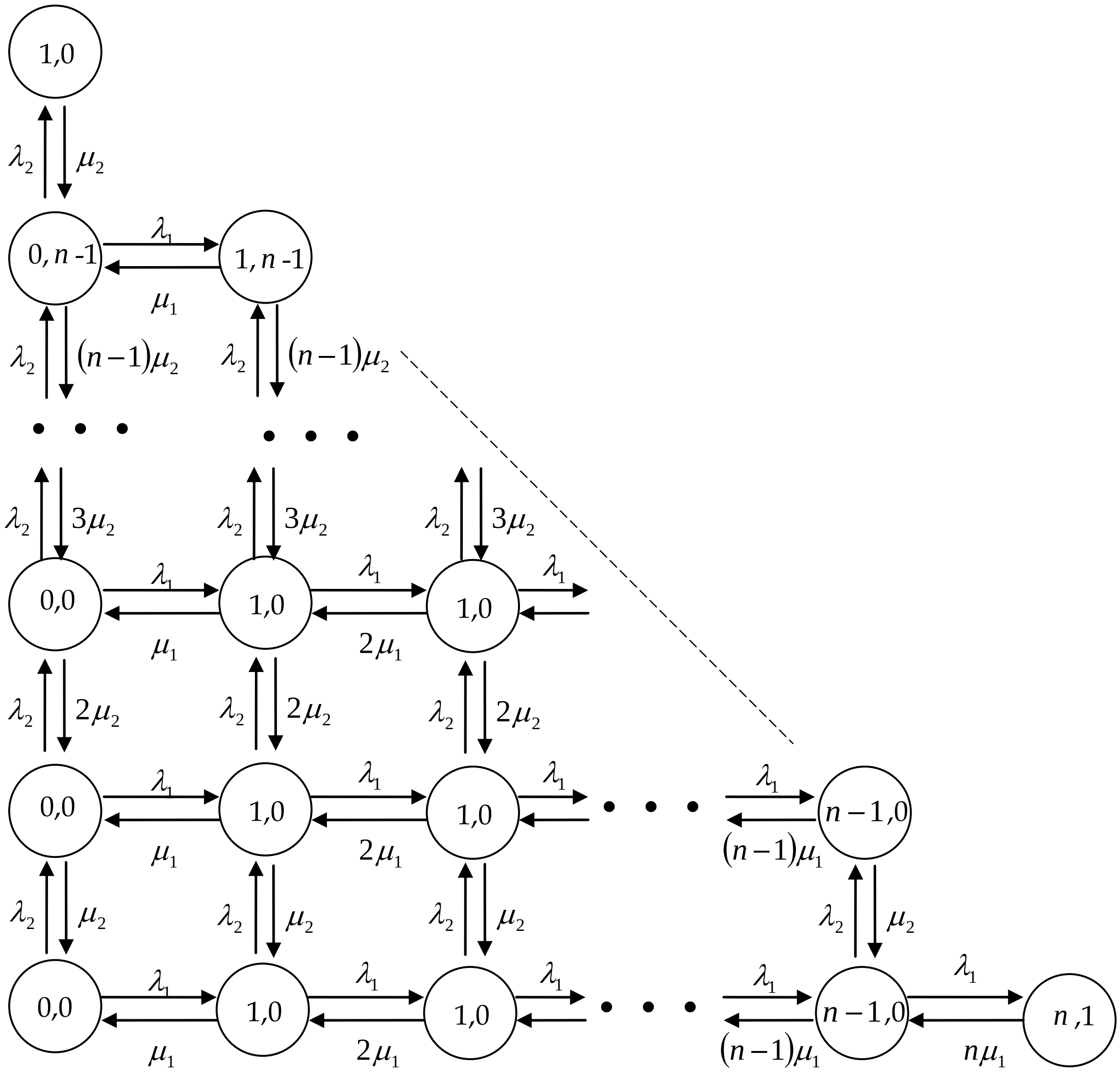


Figure 3.4 State transition diagram for a multi class Erlang loss system with two traffic streams

$$\pi(i, j) = \pi(i) \cdot \pi(j)$$

$$= G \cdot \frac{\rho_1^i}{i!} \cdot \frac{\rho_2^j}{j!} \tag{3.12}$$

where $\pi(i)$ and $\pi(i)$ are the one-dimensional truncated Poisson distributions I discussed in 3.3.1, G is the normalisation constant, and (i, j) fulfil the restrictions (3.9-3.11). As we have Poisson arrival processes, which have the PASTA-property (Poisson Arrivals See Time Averages), the time blocking probabilities, call blocking probabilities, and Erlang traffic blocking probabilities are all identical for both traffic streams, like in the one-dimensional Erlang loss model, and they are all equal to $P(i + j = n)$.

By the Binomial expansion or by convolving two Poisson distributions we find the following, where G is obtained by normalisation:

$$\pi(i + j = k) = G \frac{(\rho_1 + \rho_2)^k}{k!} \tag{3.13}$$

$$G^{-1} = \sum_{l}^{n} \frac{(\rho_1 + \rho_2)^l}{l!} \tag{3.14}$$

This is the truncated Poisson distribution with the offered traffic $\rho = \rho_1 + \rho_2$. We may also interpret this model as an Erlang loss system with one Poisson arrival process and hyper-exponentially distributed holding times in the following way. The total Poisson arrival process is a superposition of two Poisson processes with the total arrival rate $\lambda = \lambda_1 + \lambda_2$, and the holding time distribution is hyper-exponentially distributed:

$$f(t) = \frac{\lambda_1}{\lambda_1 + \lambda_2} \cdot \mu_1 \cdot e^{-\mu_1 t} + \frac{\lambda_2}{\lambda_1 + \lambda_2} \cdot \mu_2 \cdot e^{-\mu_2 t} \tag{3.15}$$

We weight the two exponential distributions according to the relative number of calls per time unit. Then the overall mean service time is

$$m = \frac{\lambda_1}{\lambda_1 + \lambda_2} \cdot \frac{1}{\mu_1} + \frac{\lambda_2}{\lambda_1 + \lambda_2} \cdot \frac{1}{\mu_2} = \frac{\rho_1 + \rho_2}{\lambda_1 + \lambda_2} = \frac{\rho}{\lambda} \tag{3.16}$$

which is in agreement with the offered traffic. Thus I have shown that Erlang's loss model is valid for hyper-exponentially distributed holding time, a special case of general insensitivity property.

The analysis can be generalised to N traffic streams:

$$\pi(i_1, i_2, \ldots, i_N) = G \cdot \frac{\rho_1^{i_1}}{i_1!} \cdot \frac{\rho_2^{i_2}}{i_2!} \cdot \ldots \cdot \frac{\rho_N^{i_N}}{i_N!}, \ 0 \le i_j \le n, \ 0 \le j \le N, \ \sum_{j=1}^{N} i_j \le n \tag{3.17}$$

This is the general multi-dimensional Erlang-B formula.

Since the numerical evaluation of the product forms will become numerically intractable for a large number of traffic classes, a simpler recursive solution for the state probabilities of the traffic model described was proposed by Kaufman and Roberts independently of each other and is named after them as Kauffman-Roberts' recursion. This recursive algorithm is also used to get the analytical values in the next section.

A validation of the simulation of two traffic types with multi-class Erlang model can be found in Appendix B.

Both Erlang loss model and multi-rate Erlang loss model will be used in the modelling of the cellular/WLAN interworking system model, which will be discussed in Chapter 6.

3.5 Erlang fixed point approximation

There is a fairly broad class of approximation techniques often referred to as reduced load approximations. The general approach is to diminish the arrival rates of offered traffic to a subnetwork (which may be a single link) by a factor equal to the probability that a new call on that route would not be blocked on the other link of its path. Typically this method leads to a set of fixed point equations for which where exists a (not necessarily unique) solution. The underlying assumption is that of independent blocking between the individual subnetworks and, although invalid in most non-trivial situations, does yield particularly good results when traffic correlations are small.

The famous Erlang fixed point approximation (EFPA) is a member of the reduced load class, one which analyses each link as a separate subnetwork. The EFPA performs well asymptotically. Kelly (1991) proved that the estimates for a network with fixed routing and no controls tend towards the exact probabilities (i) when the link capacities and arrival rates are increased simultaneously keeping the network topology fixed (Kelly limiting regime), and (ii) (Ziedins & Kelly 1989) when the number of links and routes are increased while the link loads are held constant (diverse routing limit).

The EFPA is a solution to the set of fixed point equations

$$B_j = E(\rho_j, C_j),\ j = 1,\ldots,J, \tag{3.18}$$

$$\rho_j = \sum_{r\in R} a_{j,r}\nu_r \prod_{i\in r\setminus\{j\}} (1 - B_i),\ j = 1,\ldots,J, \tag{3.19}$$

where Erlang's formula, $E(\nu, C)$, gives the probability that the Erlang loss model is fully utilised and is given by

$$E(\nu, C) = \frac{\nu^C}{C!}\left(\sum_{n=0}^{C} \frac{\nu^n}{n!}\right)^{-1} \tag{3.18}$$

The interpretation is that B_j is the probability that link j is full given its offered traffic load is ρ_j. ρ_j is an approximation obtained by considering the carried traffic on link j: the throughput of link j is $(1 - B_j)\rho_j$ and $\sum_{r\in R} a_{j,r}\nu_r(1 - L_r)$ is the sum of the contributions made by each route r to j's carried load. Applying the independent blocking assumption yields

$L_r = 1 - \Pr(\text{call accepted on each link } i \in r)$

$= 1 - \prod_{i \in r} \Pr(\text{call accepted on link } i)$

$= 1 - \prod_{i \in r} (1 - B_i)$

and the expression (5.19) follows by equating the two expressions for carried traffic on j and substituting for L_r. Kelly(1986) proved that there is a unique vector $(B_1, \ldots, B_J) \in [0,1]^J$ satisfying (3.18) and (3.19).

3.6 Summary

Before diving into the complexity of multi-cells system in which handover traffic will happen, we need to understand the traffic in a single cell with the case of single traffic type and multiple traffic type. So in this chapter I discussed and analyze the traffic in a single cell loss system. I introduced in 3.3 the Erlang loss model as a basic modelling tool for single class traffic and multi-class traffic in 3.4. I also discussed the Erlang fixed point approximation that would be very useful in solving the mathematical queueing network models.

Chapter 4 SYSTEM NETWORK DEPLOYMENT AND TOPOLOGY

4.1 Introduction

As mentioned in chapter 2, a general-purpose mathematical approach is needed for the better study of heterogeneous wireless network. In this chapter, I will discuss the network deployment in my system model, and how it can be presented in a network topological way.

4.2 Network deployment

Let's consider a cellular/WLAN interworking system in which the cellular network and WLANs will share the unused network resources to reduce the handover dropping probability to improve the connection-level QoS. In the system, one or more overlaying WLANs are deployed in a hot-spot area inside each cell of the cellular network, as shown in Figure 4.1.

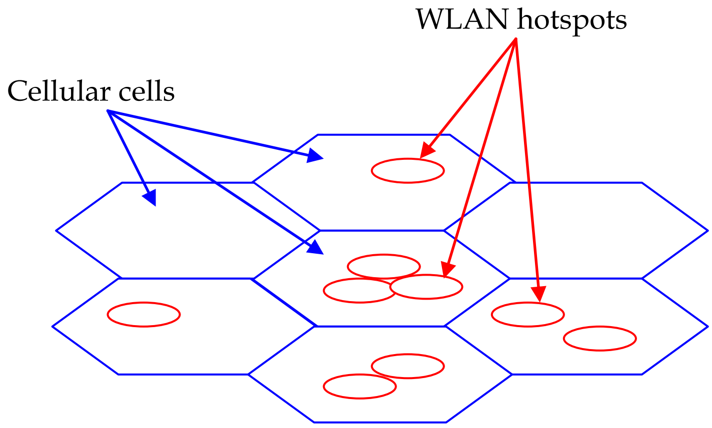


Figure 4.1 Cellular/WLAN interworking system network deployment

Cellular cells are adjacent to each other in the system providing the overall service coverage, while WLANs can be either adjacent or separate from each other with limited coverage to hot-spot areas like shopping mall, airport or a busy office. The customer mobile devices are dual-mode and equipped with network interfaces to both cellular network and WLAN [AKS04] and can thus switch between these two different networks without interrupting the service.

Both cellular access and WLAN access are available to dual-mode mobiles within the WLAN covered area. This is referred to in my thesis as double-coverage area. Because cellular networks and WLANs operate at different frequency bands, the two radio access network interfaces can be active at the same time to assist vertical handover [MSRHK98]. In contrast, the areas with only cellular radio network access are called cellular-only areas. We define coverage here to mean that the network service is available.

4.3 Network topology scheme

Such a system as described above can be mapped into the network topology graph as shown in Fig 4.2, with nodes representing each cellular cell and WLAN, and links representing the handover traffic among them. Handover can only happen when there is a link between two nodes, indicating that they are either adjacent or overlaid to each other. There are two types of links in the graph. One shown as a continuous line represents horizontal handover between homogeneous networks and the other shown as a dashed line represents vertical handover between heterogeneous networks. We can see that the two-tier overlay structure and the handover relation among different networks are well illustrated in this way.

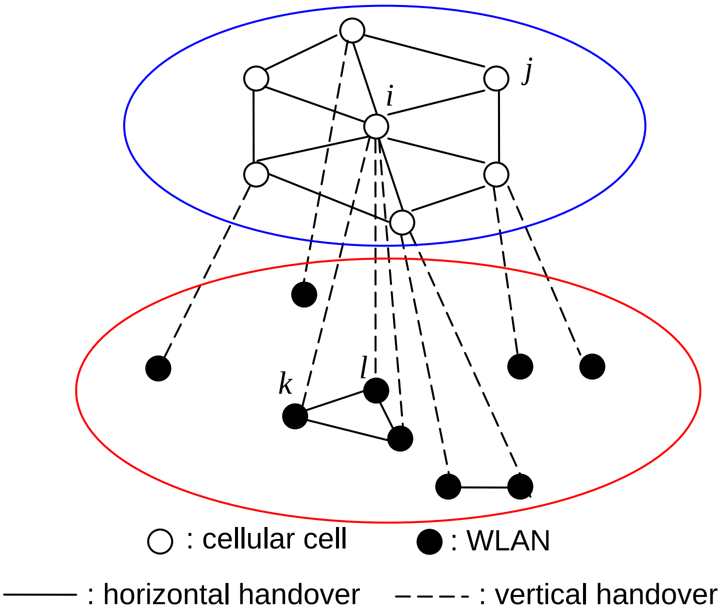
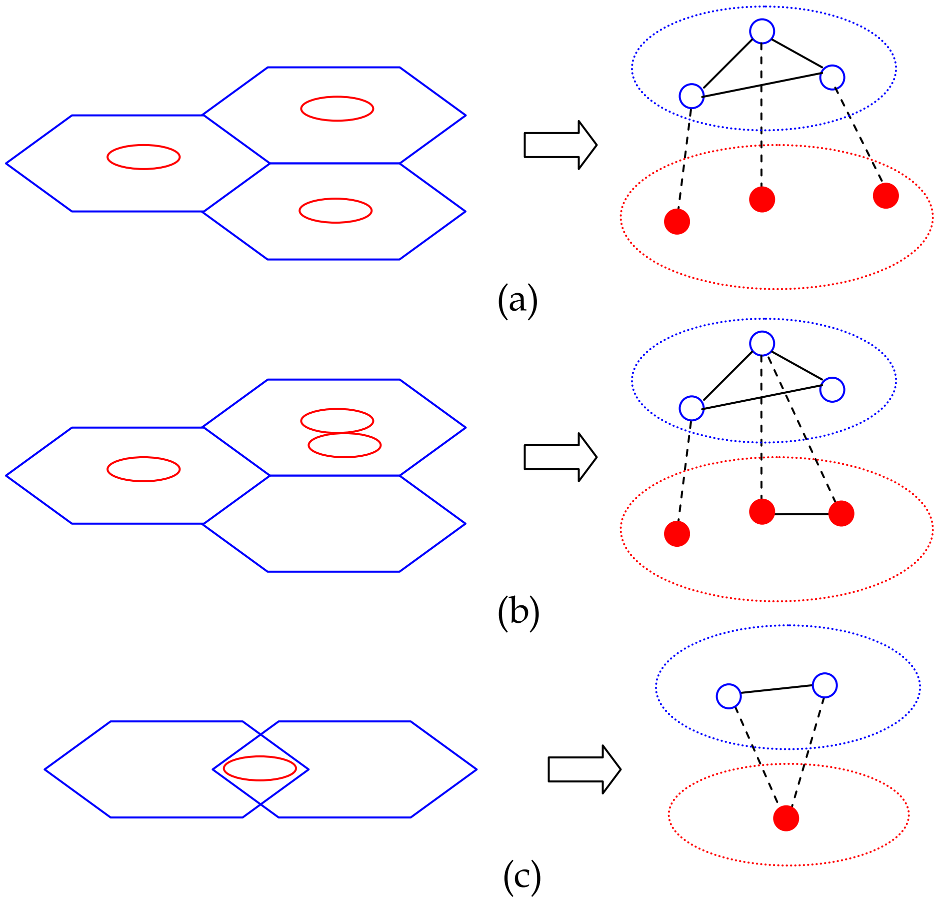


Figure 4.2 Cellular/WLAN interworking system network topology

Unlike the dynamic physical network topology used in the study of Mobile Ad-hoc NETworks (MANETs), in which each mobile terminal is modelled as a node and the links are the route the packets travel between any two mobile terminal in the signal range, the network topology here is a static logical traffic topology depicting the handover traffic relationship among different networks. Such wireless topologies are defined as *mobile-level topologies* in this thesis. The network topology idea was rarely used in the study of cellular wireless networks or infrastructure WLANs because the physical mobile-level network topology of each cell in cellular network or Basic Service Set (BSS) in WLAN is just a simple star structure. But when it is introduced into BS (Base Station)/AP (Access Point)-level we obtain a very different topology structure, which proves to be very useful in the analysis of complex handover traffic flows, as we will find out in chapter 5. This model focuses on the traffic of each base station in the cellular networks and each access point in the WLANs. We define this wireless topology as *AP/BS-level topology* as opposed to mobile-level topology.

Some examples showing how to convert an overlay wireless network into this new network topology representation are given in Figure 4.3 below. Figure 4.3 (a) shows a system consisting of 3 cellular cells and 3 WLANs with a symmetric structure, and Figure 4.3 (b) gives an example of an interworking system consisting of 3 cellular cells and 3 WLANs with an asymmetric traffic. Both of these configurations will be used in Chapter 7 for the scenario testing. Figure 4.3 (c) shows a WLAN across 2 cellular cells can also be represented using the new topology scheme.


(a)

(b)

(c)

Figure 4.3 Some examples of conversion from cellular/WLAN interworking deployment to network topology

We notice from 2.4.1 that the mobility of mobile terminals is reflected by the handover rates between adjacent nodes, so the movement of each individual mobile terminal is not our concern. Therefore the network topological structure of the system is fixed and it does not evolve with time.

4.4 Summary

In this chapter a cellular/WLAN interworking system model that will be used in the following chaters is presented. A novel network topology scheme to abstract the interworking network structure is also proposed, and its differences from the topology used in the study of MANETs are discussed. The convenience of the scheme is demonstrated through several examples.

Chapter 5 TRAFFIC ANALYSIS FOR SINGLE TRAFFIC TYPE

Based on the system model introduced in the last chapter, a study of the traffic flow both on the nodes and links of the model can be conducted.

Assume there are in total N^c cells and N^w WLANs integrated. Let us firstly define some symbols to facilitate the further analysis. Let C_i^a be the set of cells adjacent to cell i, W_i^o be the set of WLANs inside the coverage of cell i, W_k^a be the set of WLANs adjacent to WLAN k, and C_k^o be the set containing the overlaying cell of WLAN k (i.e. a double-coverage area).

The use of reservation channels or guard channels is analogous to the use of trunk reservation in fixed-wire circuit switched networks to give priority to fresh traffic over overflow traffic [DE94]. So each node can be modelled as an Erlang loss system. The service time at a node would be the channel holding time in the corresponding network the node represented.

5.1 Node Traffic Flow Analysis

Analysis is based on the conservation of traffic. Traffic flows in and out will be equal. The arriving traffic can be divided into four parts: new calls, horizontal handover calls, vertical handover calls, and overflow calls. Traffic either leaves the cell or WLAN normally by completion or handover, or due to the lack of resources are blocked or dropped. Figure 5.2 is a picture of how the traffic in each cellular cell and WLAN is distributed.

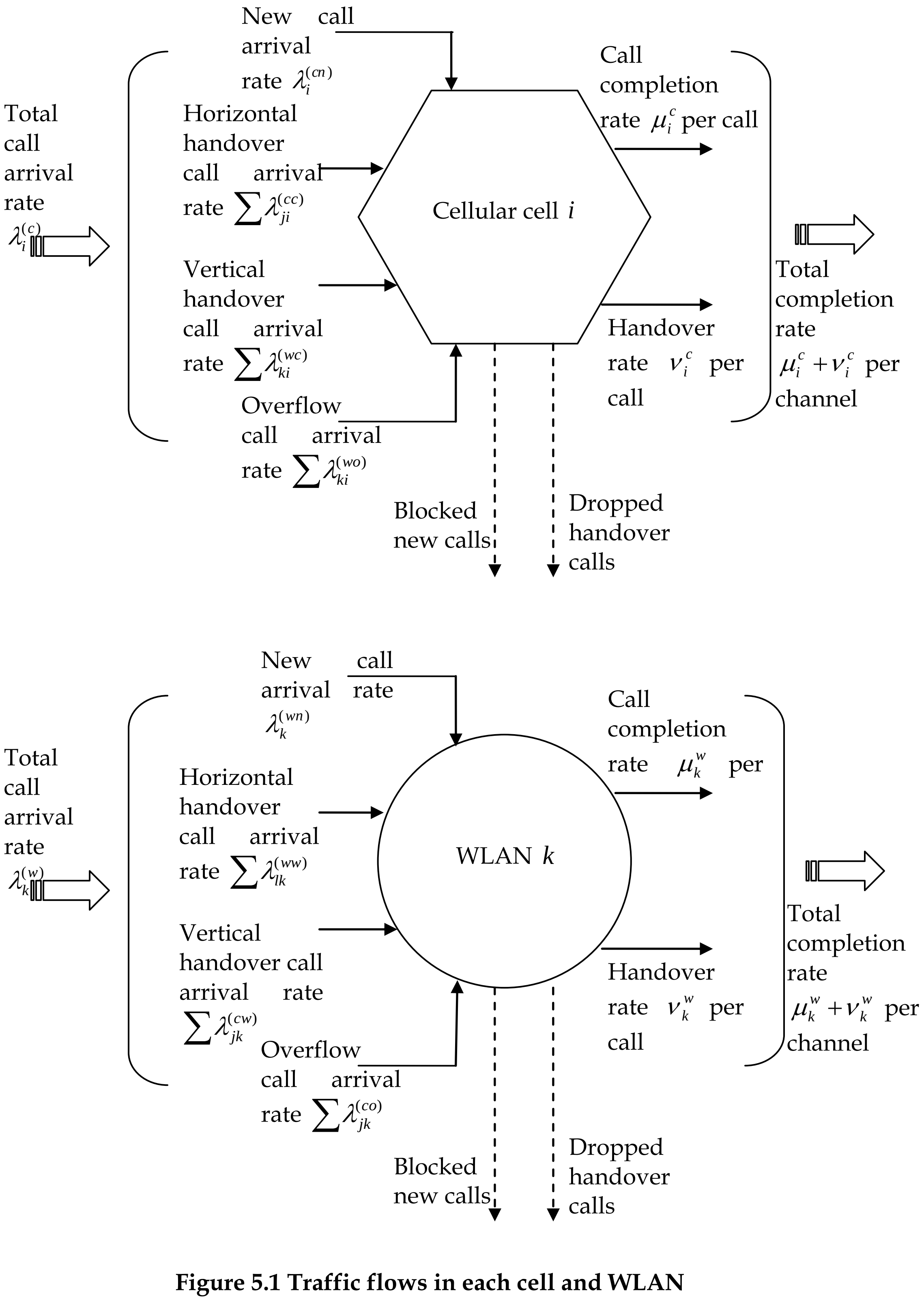


Figure 5.1 Traffic flows in each cell and WLAN

The total arrival rate at cell i is the sum of the arrival rate of new calls, handover calls (including horizontal handover calls from adjacent cells and vertical handover calls from the WLANs inside the cell) and overflow calls from WLANs within the cell.

Similarly, the total arrival rate at WLAN k is the sum of the arrival rate of new calls, handover calls (including horizontal handover calls from adjacent WLANs and vertical handover calls from the overlaid cellular cell) and overflow calls from the overlaid cell.

Symbols are summarized and provided at the start of this thesis in the list of symbols.

The new connection arrival processes to cell i and WLAN k are Poisson with rates $\lambda_i^{(cn)}$ and $\lambda_k^{(wn)}$, respectively, which are independent of other arrival processes. The channel holding time of a connection in cell i (i.e. the time that a user is using resources in cell i) is an exponential distributed random variable with mean $1/\mu_i^c$. The channel holding time in WLAN k is exponentially distributed with mean $1/\mu_k^w$. Both are independent of earlier arrival times and connection holding times.

At the end of a holding time, a connection in cell i of the cellular system may terminate and leave the system with probability $T_i^{(c)}$, or move within the system and continue in an adjacent cell or WLAN with probability $1-T_i^{(c)}$. The probability that a connection continues and moves to an adjacent cell of cell i or WLAN k inside cell i is $1-T_i^{(c)} = \sum_{j \in C_i^a} H_{ij}^{(cc)} + \sum_{k \in W_i^o} H_{ik}^{(cw)}$, where $H_{ij}^{(cc)}$ is the probability of attempting a horizontal handover to adjacent cell j, and $H_{ik}^{(cw)}$ is the probability of attempting a vertical handover to WLAN k inside cell i.

Similarly, at the end of a holding time of a connection in WLAN k, a call may terminate and leave the system with probability $T_k^{(w)}$, or move within the system and continue in an adjacent WLAN or an overlay cell of the cellular system with probability $1-T_k^{(w)}$. The probability that a connection continues and moves to an adjacent WLAN to WLAN k or overlaying cell i is $1-T_k^{(w)} = \sum_{l \in W_k^a} H_{kl}^{(ww)} + \sum_{i \in C_k^o} H_{ki}^{(wc)}$, where $H_{kl}^{(ww)}$ is the probability of attempting a horizontal handover to adjacent

WLAN l, and $H_{ki}^{(wc)}$ is the probability of attempting a vertical handover to overlaying cell i.

Each cell i of the cellular system has a capacity of C_i^c units of bandwidth. While each WLAN k has a capacity of C_k^w units of bandwidth. I define R_i^c and R_k^w as the reservation parameters of cell i and WLAN k for handover calls respectively. They act as the admission policy to provide handover connections priority over new connections. Two admission schemes are considered: the cut-off priority and the fractional guard channel.

Let n_i be the number of connections in cell i. When cell i is in any of the states $n_i \leq C_i^c - R_i^c$, it accepts new and handover calls under both admission policies. When cell i is in any of the states $n_i > C_i^c - R_i^c$, only handover requests are accepted for the cut-off priority scheme. For the fractional guard channel scheme, besides handover requests, each new connection request is also accepted with probability ω_i^c. The same admission policies apply to WLANs with probability ω_k^w. Note that cut-off priority is a particular case of the fractional guard channel with $\omega_k^w = 0$. If a handover request is not accepted in one network, then the request is transferred to the other network. In the cellular system, only when the user is inside the dual-coverage area can the connection be transferred to the WLAN. Connections that are within the WLAN can always be attempted to be transferred to the corresponding overlaying cell in the cellular system.

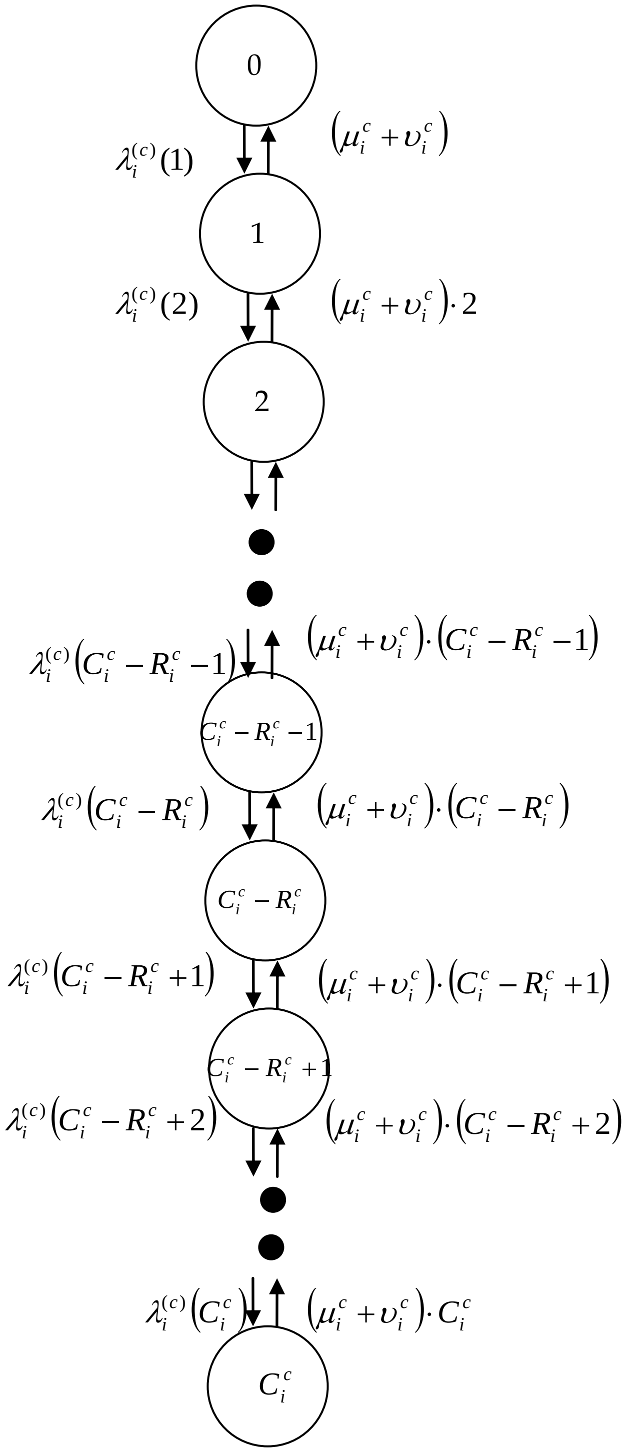


Figure 5.2 State transition diagram for the cellular cell

The occupancy of a cell evolves according to a birth-death process independent of other cells as shown in Fig 5.2. The process for cell i evolves with birth rate ρ_i^c (5.1 a) for the unreserved states and α_i^c (5.1 b) for the reserved states. The death rate of cell i in state n_i is $n_i\mu_i^c$. The total traffic offered to cell i in state n_i is

$$\lambda_i^c(k_i^c) = \begin{cases} \lambda_i^{(cn)} + \sum\limits_{j \in C_i^a} \lambda_{ji}^{(cc)} + \sum\limits_{k \in W_i^o} \lambda_{ki}^{(wc)} + \sum\limits_{l \in W_i^o} \lambda_{li}^{(wo)}, \quad k_i^c \le C_i^c - R_i^c & (a) \\ \lambda_i^c \omega_i^c + \sum\limits_{j \in C_i^a} \lambda_{ji}^{(cc)} + \sum\limits_{k \in W_i^o} \lambda_{ki}^{(wc)} + \sum\limits_{l \in W_i^o} \lambda_{li}^{(wo)}, \quad k_i^c > C_i^c - R_i^c & (b) \end{cases} \tag{5.1}$$

with $\omega_i^c = 0$ for the cut-off priority scheme, and $0 \le \omega_i^c \le 1$ for the fractional guard channel scheme. The term $\lambda_{ji}^{(cc)}$ is the horizontal handover rate of cell j offered to cell i, for adjacent cells i and j, and $\lambda_{ki}^{(wc)}$ is the vertical handover rate of WLAN k offered to overlaid cell i, $\lambda_{zk}^{(co)}$ is the proportion of all handover traffic that is not accepted in cell z due to the resource depletion and thence overflowed to WLAN k.

Similarly, the occupancy of WLAN k evolves with birth rates ρ_k^w (5.2 a) and α_k^w (5.2 b) based on the state m_k, and death rate $k_k^w\left(\mu_k^w + \upsilon_k^w\right)$. The total traffic offered to WLAN k in state k_k^w is

$$\lambda_k^w\left(k_i^w\right) = \begin{cases} \lambda_k^{(wn)} + \sum\limits_{l \in W_k^a} \lambda_{lk}^{(ww)} + \sum\limits_{j \in C_k^o} \lambda_{jk}^{(cw)} + \sum\limits_{g \in C_k^o} \lambda_{gk}^{(co)}, \quad m_k \le C_k^w - R_k^w & (a) \\ \lambda_k^w \omega_k^w + \sum\limits_{l \in W_k^a} \lambda_{lk}^{(ww)} + \sum\limits_{j \in C_k^o} \lambda_{jk}^{(cw)} + \sum\limits_{g \in C_k^o} \lambda_{gk}^{(co)}, \quad m_k > C_k^w - R_{k\ i}^{wc} & (b) \end{cases} \tag{5.2}$$

5.2 Link Traffic Flow (Handover Traffic) Analysis

Let's now focus on the traffic flow on the links, i.e., handover traffic and overflow traffic to derive the handover rates in (5.1 a, b) and (5.2 a, b). It will be found that the handover rates and the blocking rate and dropping rate are inter-dependent with each other.

5.2.1 Handover calls to cell

The horizontal handover rate $\lambda_{ji}^{(cc)}$ of cell j offered to cell i, for adjacent cells i and j, is all the non-blocked (dropped) traffic in cell j multiply with a handover probability factor and is shown in the figure 5.3.

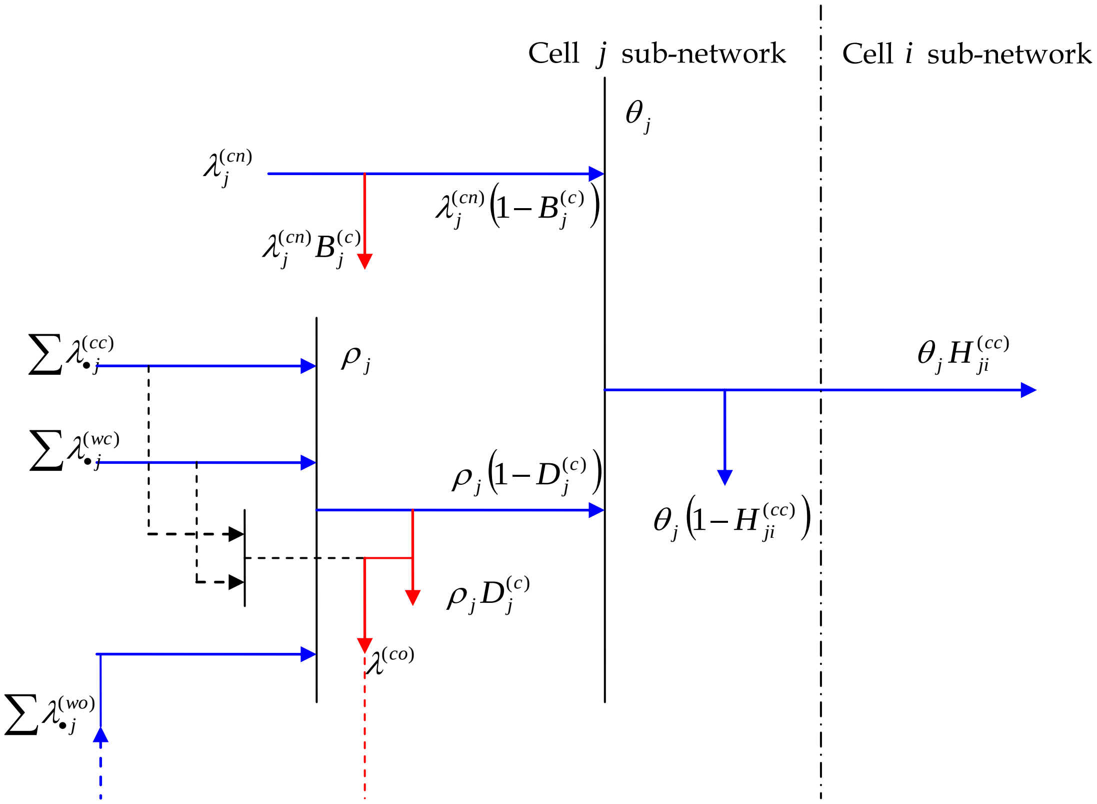


Figure 5.3 Horizontal handover traffic between cellular cells

So the formula for horizontal handover is given by equation 5.3.

$$\lambda_{ji}^{(cc)} = H_{ji}^{(cc)} \cdot \left[\lambda_j^{(cn)} \cdot \left(1-B_j^{(c)}\right) + \left(\sum_{x\in C_j^a} \lambda_{xj}^{(cc)} + \sum_{y\in W_j^o} \lambda_{yj}^{(wc)} + \sum_{z\in W_j^o} \lambda_{zj}^{(wo)} \right) \cdot \left(1-D_j^{(c)}\right) \right] \tag{5.3}$$

where $B_j^{(c)}$ and $D_j^{(c)}$ are the new connection blocking and handover dropping probabilities in cell j, respectively.

In equation (5.3), $\lambda_{zj}^{(wo)}$ corresponds to all handover traffic that is not accepted in WLAN z and hence transferred to cell j, so

$$\lambda_{zj}^{(wo)} = D_z^{(w)} \cdot \left(\lambda_{jz}^{(cw)} + \sum_{l\in W_z^a} \lambda_{lz}^{(ww)} \right) \tag{5.4}$$

For $\lambda_{ki}^{(wc)}$, the vertical handover rate of WLAN k offered to overlay cell i is given by

$$\lambda_{ki}^{(wc)} = H_{ki}^{(wc)} \cdot \left[\lambda_k^{(wn)} \cdot \left(1 - B_k^{(w)}\right) + \left(\sum_{x \in W_k^a} \lambda_{xk}^{(ww)} + \sum_{y \in C_k^o} \lambda_{yk}^{(cw)} + \sum_{z \in C_k^o} \lambda_{zk}^{co} \right) \cdot \left(1 - D_k^{(w)}\right) \right] \tag{5.5}$$

where $B_k^{(w)}$ and $D_k^{(w)}$ are the new connection blocking and handover dropping probabilities in WLAN k, respectively.

In (5.6), $\lambda_{zk}^{(co)}$ is the proportion of all handover traffic that is not accepted in cell z and thence transferred to WLAN k, then

$$\lambda_{zk}^{(co)} = D_z^{(c)} \cdot \left(\lambda_{kz}^{(wc)} + \sum_{l \in C_z^a} \lambda_{lz}^{(cc)} \right) \cdot \gamma_{zk} \tag{5.6}$$

Where γ_{zk} is the coverage factor between WLAN k and overlay cell z, i.e. the ratio between the radio coverage area of WLAN k and the radio coverage area of cell z with $0 < \gamma_{zk} \le 1$.

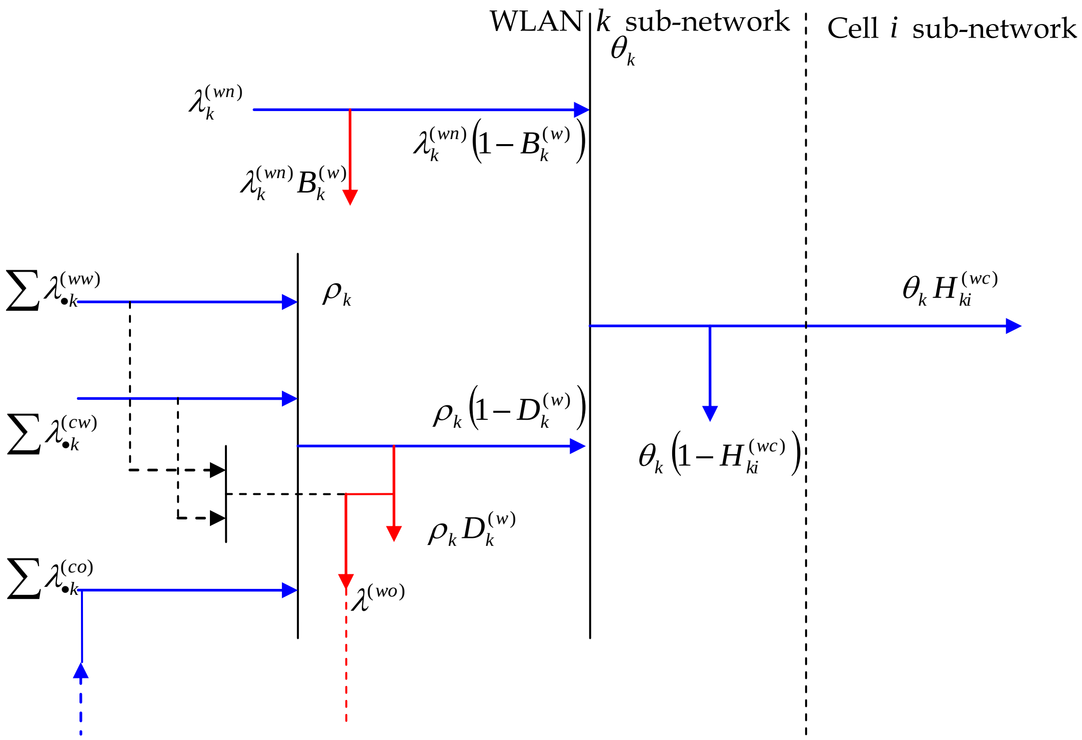


Figure 5.4 Vertical handover traffic from WLAN to cellular cell

5.2.2 *Handover calls to WLAN*

Similarly, we can derive the term $\lambda_{lk}^{(ww)}$, the horizontal handover rate of WLAN l offered to WLAN k, for adjacent WLAN l and k, which is given by

$$\lambda_{lk}^{(ww)} = H_{lk}^{(ww)} \cdot \left[\lambda_l^{(wn)}\left(1-B_l^{w}\right) + \left(\sum_{x\in W_l^a} \lambda_{xl}^{(ww)} + \sum_{y\in C_l^o} \lambda_{yl}^{(cw)} + \sum_{z\in C_l^o} \lambda_{zl}^{(co)} \right) \cdot (1-D_l^{w}) \right] \tag{5.7}$$

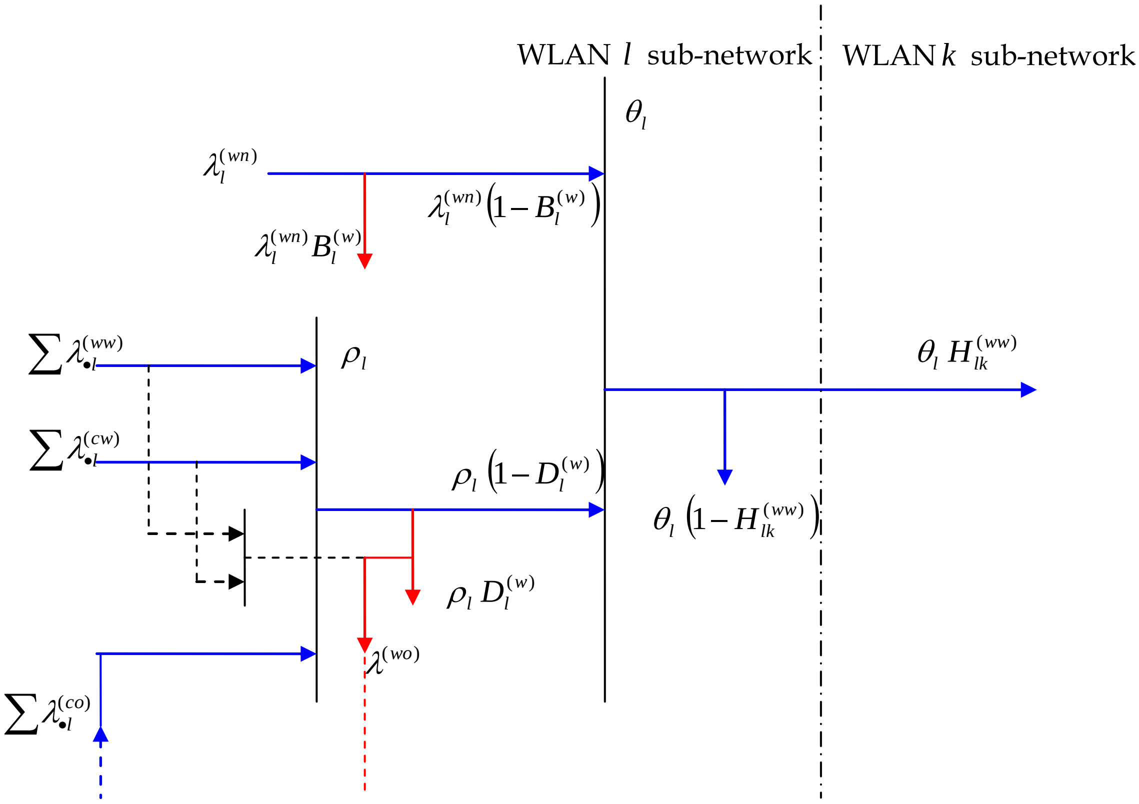


Figure 5.5 Horizontal handover traffic betweenWLANs

The term $\lambda_{jk}^{(cw)}$ is the vertical handover rate of cell j offered to WLAN k, for overlaying cell j and k, and is given by

$$\lambda_{jk}^{(cw)} = H_{jk}^{(cw)} \cdot \left[\lambda_j^{(cn)}\left(1-B_j^{c}\right)\gamma_{jk} + \left(\sum_{x\in C_j^a} \lambda_{xj}^{(cc)}\gamma_{jk} + \sum_{y\in W_j^o} \upsilon_{yj}^{(wc)}\gamma_{jk} + \sum_{z\in W_j^o} \lambda_{zj}^{(wo)} \right) \cdot (1-D_j^{c}) \right] \tag{5.8}$$

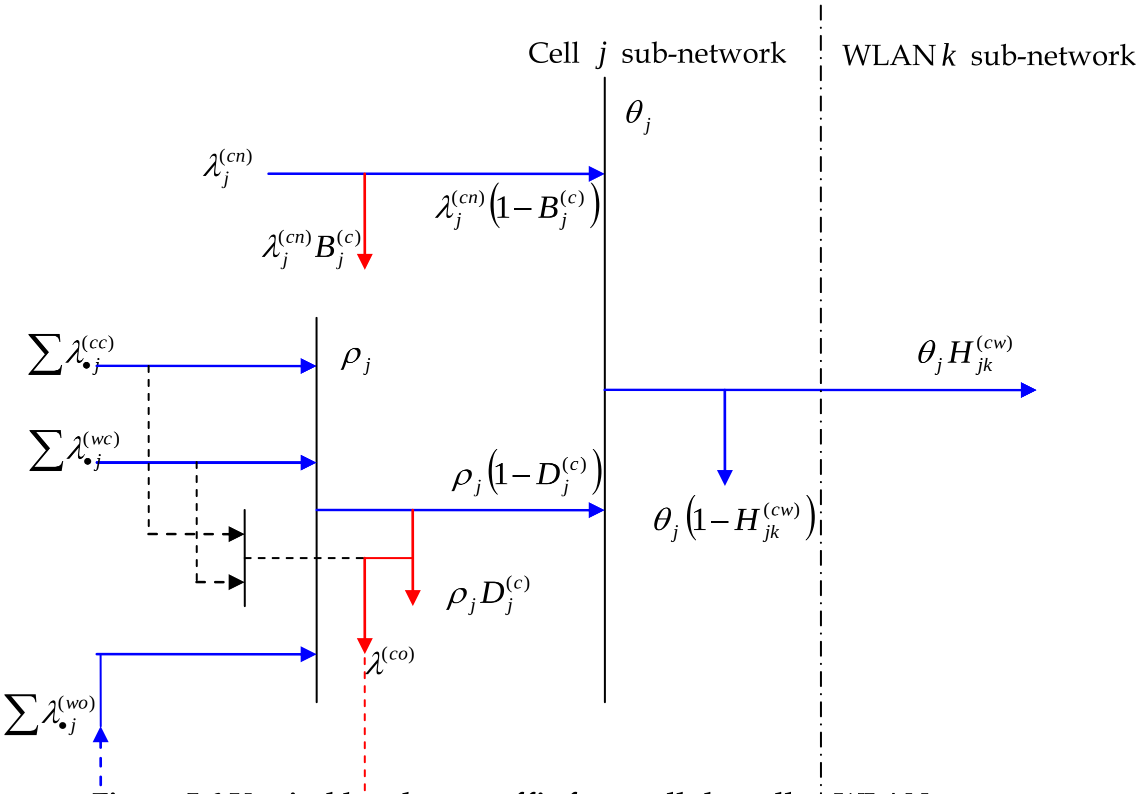


Figure 5.6 Vertical handover traffic from cellular cell to WLAN

5.3 Balance Equations

From the analysis of the birth-death process in cell i, the detailed balance equations are

$$\pi_i^c\left(k_i^c-1\right)\cdot\left(\lambda_i^{(cn)}+\sum_{j\in C_i^a}\lambda_{ji}^{(cc)}+\sum_{k\in W_i^o}\lambda_{ki}^{(wc)}+\sum_{l\in W_i^o}\lambda_{li}^{(wo)}\right)=\pi_i^c\left(k_i^c\right)k_i^c(\mu_i^c+\upsilon_i^c),\quad 0<k_i^c\le C_i^c-R_i^c \tag{5.9}$$

$$\pi_i^c\left(k_i^c-1\right)\cdot\left(\lambda_i^{(cn)}\omega_i^c+\sum_{j\in C_i^a}\lambda_{ji}^{(cc)}+\sum_{k\in W_i^o}\lambda_{ki}^{(wc)}+\sum_{l\in W_i^o}\lambda_{li}^{(wo)}\right)=\pi_i^c\left(k_i^c\right)k_i^c(\mu_i^c+\upsilon_i^c),\quad C_i^c-R<k_i^c\le C_i^c \tag{5.10}$$

where $\pi_i^c\left(k_i^c\right)$ is the steady state probability that there are k_i^c calls is in cell i, and is derived as

$$\pi_i^c\left(k_i^c\right)=\frac{\left(\lambda_i^{(cn)}+\sum_{j\in C_i^a}\lambda_{ji}^{(cc)}+\sum_{k\in W_i^o}\lambda_{ki}^{(wc)}+\sum_{l\in W_i^o}\lambda_{li}^{(wo)}\right)^{k_i^c}}{\pi_i^c(0)k_i^c!\left(\mu_i^c+\upsilon_i^c\right)^{k_i^c}}, \quad n_i\le C_i^c-R_i^c \tag{5.11}$$

$$\pi_i^c\left(k_i^c\right)=\frac{\left(\lambda_i^{(cn)}+\sum_{j\in C_i^a}\lambda_{ji}^{(cc)}+\sum_{k\in W_i^o}\lambda_{ki}^{(wc)}+\sum_{l\in W_i^o}\lambda_{li}^{(wo)}\right)^{C_i^c-R_i^c}\left(\lambda_i^{(cn)}+\sum_{j\in C_i^a}\lambda_{ji}^{(cc)}+\sum_{k\in W_i^o}\lambda_{ki}^{(wc)}+\sum_{l\in W_i^o}\lambda_{li}^{(wo)}\right)^{k_i^c-C_i^c+R_i^c}}{\pi_i^c(0)k_i^c!\left(\mu_i^c+\upsilon_i^c\right)^{k_i^c}}$$
$$, \quad n_i>C_i^c-R_i^c \tag{5.12}$$

where $\pi_i^c(0)$ is the normalisation constant, obtained as

$$\pi_i^c(0)=\sum_{k_i^c=0}^{C_i^c-R_i^c}\frac{1}{k_i^c!}\left(\frac{\lambda_i^{(cn)}+\sum_{j\in C_i^a}\lambda_{ji}^{(cc)}+\sum_{k\in W_i^o}\lambda_{ki}^{(wc)}+\sum_{l\in W_i^o}\lambda_{li}^{(wo)}}{\mu_i^c+\upsilon_i^c}\right)^{k_i^c}$$
$$+\sum_{n_i=C_i^c-R_i^c+1}^{C_i^c}\frac{\left(\lambda_i^{(cn)}+\sum_{j\in C_i^a}\lambda_{ji}^{(cc)}+\sum_{k\in W_i^o}\lambda_{ki}^{(wc)}+\sum_{l\in W_i^o}\lambda_{li}^{(wo)}\right)^{C_i^c-R_i^c}\left(\lambda_i^{(cn)}\omega_i^c+\sum_{j\in C_i^a}\lambda_{ji}^{(cc)}+\sum_{k\in W_i^o}\lambda_{ki}^{(wc)}+\sum_{l\in W_i^o}\lambda_{li}^{(wo)}\right)^{k_i^c-C_i^c+R_i^c}}{k_i^c!\left(\mu_i^c+\upsilon_i^c\right)^{n_i}} \tag{5.13}$$

From the process WLAN k, the detailed balance equations are

$$\pi_k^w\left(k_k^w-1\right)\left(\lambda_k^{(wn)}+\sum_{l\in W_k^a}\lambda_{lk}^{(ww)}+\sum_{j\in C_k^o}\lambda_{jk}^{(cw)}+\sum_{g\in C_k^o}\lambda_{gk}^{(co)}\right)=\pi_k^w\left(k_k^w\right)k_k^w(\mu_k^w+\upsilon_k^w), \quad 0<k_k^w\le C_k^w-R_k^w \tag{5.14}$$

$$\pi_k^w\left(k_k^w-1\right)\left(\lambda_k^{(wn)}\omega_k^w+\sum_{l\in W_k^a}\lambda_{lk}^{(ww)}+\sum_{j\in C_k^o}\lambda_{jk}^{(cw)}+\sum_{g\in C_k^o}\lambda_{gk}^{(co)}\right)=\pi_k^w\left(k_k^w\right)k_k^w(\mu_k^w+\upsilon_k^w), \quad C_k^w-R<k_k^w\le C_k^w \tag{5.15}$$

Where $\pi_k^w\left(k_k^w\right)$ is the steady state probability that k_k^w calls is in WLAN k, and is derived as

$$\pi_k^w\left(k_k^w\right)=\frac{\left(\lambda_k^{(wn)}+\sum_{l\in W_k^a}\lambda_{lk}^{(ww)}+\sum_{j\in C_k^o}\lambda_{jk}^{(cw)}+\sum_{g\in C_k^o}\lambda_{gk}^{(co)}\right)^{k_k^w}}{\pi_k^w(0)k_k^w!\left(\mu_k^w+\upsilon_k^w\right)^{k_k^w}},\quad k_k^w\le C_k^w-R_k^w \tag{5.16}$$

$$\pi_k^w\left(k_k^w\right)=\frac{\left(\lambda_k^{(wn)}+\sum_{l\in W_k^a}\lambda_{lk}^{(ww)}+\sum_{j\in C_k^o}\lambda_{jk}^{(cw)}+\sum_{g\in C_k^o}\lambda_{gk}^{(co)}\right)^{C_k^w-R_k^w}\left(\lambda_k^{(wn)}\omega_k^w+\sum_{l\in W_k^a}\lambda_{lk}^{(ww)}+\sum_{j\in C_k^o}\lambda_{jk}^{(cw)}+\sum_{g\in C_k^o}\lambda_{gk}^{(co)}\right)^{k_k^w-C_k^w+R_k^w}}{\pi_k^w(0)k_k^w!\left(\mu_k^w+\upsilon_k^w\right)^{k_k^w}}$$
$$,\quad k_k^w>C_k^w-R_k^w \tag{5.17}$$

where $\pi_k^w(0)$ is the normalisation constant, obtained as

$$\pi_k^w(0)=\sum_{k_k^w=0}^{C_k^w-R_k^w}\frac{1}{k_k^w!}\left(\frac{\lambda_k^{(wn)}+\sum_{l\in W_k^a}\lambda_{lk}^{(ww)}+\sum_{j\in C_k^o}\lambda_{jk}^{(cw)}+\sum_{g\in C_k^o}\lambda_{gk}^{(co)}}{\mu_k^w+\upsilon_k^w}\right)^{k_k^w}+$$
$$\sum_{k_k^w=C_k^w-R_k^w+1}^{C_k^w}\frac{\left(\lambda_k^{(wn)}+\sum_{l\in W_k^a}\lambda_{lk}^{(ww)}+\sum_{j\in C_k^o}\lambda_{jk}^{(cw)}+\sum_{g\in C_k^o}\lambda_{gk}^{(co)}\right)^{C_k^w-R_k^w}\left(\lambda_k^{(wn)}\omega_k^w+\sum_{l\in W_k^a}\lambda_{lk}^{(ww)}+\sum_{j\in C_k^o}\lambda_{jk}^{(cw)}+\sum_{g\in C_k^o}\lambda_{gk}^{(co)}\right)^{k_k^w-C_k^w+R_k^w}}{k_k^w!\left(\mu_k^w+\upsilon_k^w\right)^{k_k^w}} \tag{5.18}$$

5.4 QoS Metrics

In the cellular system the new-connection blocking probability $B_i^{(c)}$ in cell i is $B_i^{(c)}=\sum_{k_i^c=C_i^c-R_i^c}^{C_i^c-1}\pi_i^c\left(n_i\right)\left(1-\omega_i^c\right)+\pi_i^c\left(C_i^c\right)$, and the handover dropping probability $D_i^{(c)}=\pi_i^c\left(C_i^c\right)$.

Similarly, $B_k^{(w)}$ in WLAN k is $B_k^{(w)}=\sum_{K_k^w=C_k^w-R_k^w}^{C_c^w-1}\pi_k^w\left(m_k\right)\left(1-\omega_k^w\right)+\pi_k^w\left(C_k^w\right)$, and $D_k^{(w)}=\pi_k^w\left(C_k^w\right)$.

As we can see, blocking probabilities $B_i^{(c)}$, $B_k^{(w)}$ and dropping probabilities $D_i^{(c)}$, $D_k^{(w)}$ and handover rates are inter-dependent, so they can be calculated numerically using Erlang Fixed-Point Approximation discussed in Chapter 3. I first give blocking probabilities $B_i^{(c)}$, $B_k^{(w)}$ and dropping probabilities $D_i^{(c)}$, $D_k^{(w)}$ an initial value, then I calculate the values of the handover rates in each cellular cell and WLAN. With handover rates I then get the new blocking probabilities $B_i^{(c)}$, $B_k^{(w)}$ and dropping probabilities $D_i^{(c)}$, $D_k^{(w)}$ using the Erlang-B formula. Then I compare the new blocking and dropping probabilities with the old ones, if they are less than a given threshold, they can be accepted, otherwise all the above steps will be repeated once again using the obtained blocking and dropping probabilities as the new initial inputs. Scenarios based on this model and the results will be given in chapter 7.

5.5 Summary

In this chapter, I analysed a single rate traffic cellular/WLAN integrated wireless network based on the system model discussed in chapter 4. A detailed study of the node traffic flow is given in 5.1 and link traffic analysis in 5.2 based on the network topology scheme. I gave the QoS metrics that will be considered in our model and discussed calculated using the Erlang fixed point approximation. This transforms the network problem into finally a set of non-linear equations. By solving this set of equations the performance of the system in terms of new call blocking probability and handover call dropping probability can be easily derived.

Chapter 6 MULTI RATE TRAFFIC FLOW ANALYSIS

6.1 Introduction

In the last chapter, a system model for cellular/WLAN interworking with single rate traffic was developed and analysed. In this chapter, a more complex multi rate traffic case will be analysed.

Similar to the setting in the last chapter, M^c is defined as the set of all cellular cell nodes (nodes in white as shown in Figure 4.2); C_i^a as the set of cellular cell nodes connected to cell node i, i.e., all the cells adjacent to cell i, W_i^o as the set of WLAN nodes connected to cell node i, i.e., all the WLANs inside the coverage area of cell i; W_k^a as the set of WLAN nodes connected to WLAN node k, i.e., all the WLANs adjacent to WLAN k; and C_k^o as the set of cellular cell nodes connected to WLAN node k, i.e., all the overlaying cells of WLAN k (i.e. a dual cellular/WLAN coverage area).

6.2 Node Traffic Flow Analysis

Based on the conservation of traffic, traffic flows in and out will be equal. The arrival traffic consists of four components: new calls, horizontal handover calls, vertical handover calls, and overflow calls. E is the set of all the service classes. Traffic either leaves the cell node or WLAN node by completion or handover, or due to the lack of resources are blocked or dropped as shown in Figure 5.2.

There is more than one type of traffic; each service type $e \in E$ requires b_k basic bandwidth units (BBU) to fully satisfy its QoS requirements. It is assumed that the fixed bandwidth requirement upon arrival. New call requests for service type e arrive at cellular cell node i and WLAN node k according to independent Poisson processes with rates $\lambda_{i,e}^{(cn)}$ and $\lambda_{k,e}^{(wn)}$, respectively. The duration of each call of service type e is defined as connection time t_e. We assume that t_e is an exponentially distributed random variable with mean $1/\upsilon_e$. Because of the memoryless property of exponential distribution, the residual (i.e., remaining) connection time t_e^R is also exponentially distributed with mean $1/\upsilon_e$.

To model the mobility, the inter-boundary time can be defined, similar to [IA02], as the time interval between any two consecutive access network boundaries crossing by a mobile user. The wider the coverage areas or the slower moving the users, the longer the inter-boundary times are. If an inter-boundary time starts at the moment of entering cell i, then we denote it by $t_{b_i}^c$. If an inter-boundary time starts at the moment of entering WLAN k, then we denote it by $t_{b_k}^w$. We assume that $t_{b_i}^c$ and $t_{b_k}^w$ are exponentially distributed with means $1/\eta_i^c$ and $1/\eta_k^w$, respectively.

The channel holding time can be defined as the time that a connected mobile user keeps using BBU resources in each network. For service e, the channel holding times in cell i and in WLAN k are obtained as $\min\left(t_e^R, t_{b_i}^c\right)$ and $\min\left(t_e^R, t_{b_k}^w\right)$, respectively. Since t_e^R, $t_{b_i}^c$, and $t_{b_k}^w$ have exponential distributions for all $e \in E$, $i \in M^c$ and $k \in W_i^c$, the channel holding times are also exponentially distributed with parameters $\mu_{i,e}^c = \upsilon_e + \eta_i^c$ and $\mu_{k,e}^w = \upsilon_e + \eta_k^w$, respectively.

A mobile user who is holding a connection of service type e in cell i may terminate this connection at the end of its holding time and leave the cellular/WLAN system with probability $T_{i,e}^c = \upsilon_e / \left(\upsilon_e + \eta_i^c\right)$. It may also move within the system and continue in an adjacent cell or an underlying WLAN with probability $1 - T_{i,e}^c$. So (6.1) can be derived

$$1 - T_{i,e}^c = \frac{\eta_i^c}{\upsilon_e + \eta_i^c} = \sum_{j \in C_i^a} H_{ij,e}^{cc} + \sum_{k \in W_i^o} H_{ik,e}^{cw} \tag{6.1}$$

Where $H_{ij,e}^{cc}$ denotes the probability of attempting a horizontal handover from cell i to adjacent cell j, and $H_{ik,e}^{cw}$ denotes the probability of attempting a vertical handover from cell i to WLAN k inside the cell i.

On the other hand, a mobile user who is holding a connection of service e in WLAN k may terminate its connection at the end of its holding time and leave the cellular/WLAN system with probability $T_{k,e}^{w} = \upsilon_e / \left(\upsilon_e + \eta_k^{w} \right)$. It may also move within the system and continue in an adjacent cell or an underlying WLAN with probability $1 - T_{k,e}^{w}$. So (6.2) can be derived.

$$1 - T_{k,e}^{w} = \frac{\eta_k^{w}}{\upsilon_e + \eta_k^{w}} = \sum_{j \in W_k^a} H_{kl,e}^{ww} + \sum_{i \in C_k^o} H_{ki,e}^{wc} \tag{6.2}$$

Where $H_{kl,e}^{ww}$ denotes the probability of attempting a horizontal handover from WLAN k to adjacent WLAN l, and $H_{ki,e}^{wc}$ denotes the probability of attempting a vertical handover from WLAN k to its overlaying cell i.

The occupancy of a node evolves to a multi-dimensional birth-death process independent of other nodes. The birth rate (i.e., the rate of occurring a birth event) of service e in the birth-death process corresponding to cell i is $\lambda_{i,e}^{c}$.

$$\lambda_{i,e}^{c} = \lambda_{i,e}^{cn} \left(1 - \beta_{i,e}^{cn} \left(m_i^c \right) \right) + [\sum_{j \in C_i^a} \lambda_{ji,e}^{cc} + \sum_{k \in W_i^o} \lambda_{ki,e}^{wc} + \sum_{k \in W_i^o} \lambda_{ki,e}^{wo}] \left(1 - \beta_{i,e}^{ch} \left(m_i^c \right) \right) \tag{6.3}$$

Similarly, let $\phi_{k,e}^{w}$ denote the birth rate of service type e in the process corresponding to WLAN k. So (6.9) and (6.10) can be derived.

$$\lambda_{k,e}^{w} = \lambda_{k,e}^{wn} \left(1 - \beta_{k,e}^{wn} \left(m_k^w \right) \right) + [\sum_{l \in W_k^a} \lambda_{lk,e}^{ww} + \sum_{i \in C_k^o} \lambda_{ik,e}^{cw} + \sum_{i \in C_k^o} \lambda_{ik,e}^{co}] \left(1 - \beta_{k,e}^{wh} \left(m_k^w \right) \right) \tag{6.4}$$

6.3 Link Traffic Flow (Handover Traffic) Analysis

Each cell i of the cellular system is assumed to have a capacity of C_i^c BBUs. Let $m_{i_s}^{c}$ denote the number of connections of multimedia service s in cell i. The capacity constraint requires that,

$$\sum_{e \in E} m_{i,e}^{c} b_e \le C_i^c, \qquad \forall i \in M^c \tag{6.5}$$

From (3), there can be at most $\lfloor C_i^c / b_e \rfloor$ connections of service e in cell i at any time. We define $m_i^c = \left(m_{i,1}^c, m_{i,2}^c, \cdots, m_{i,E}^c\right)$ as the channel occupancy vector in cell i. For each cell $i \in M^c$, admission control policies on connection requests from new and handover users for service $e \in E$ can be modeled by policy function $\beta_{i,e}^{cn}\left(m_i^c\right)$ and $\beta_{i,e}^{ch}\left(m_i^c\right)$, respectively. A policy function $\beta_{i,e}^{cn}\left(m_i^c\right)$ determines the probability of blocking of a connection request from a new user for service e in cell i. Similarly, policy function $\beta_{i,e}^{ch}\left(m_i^c\right)$ determines the probability of blocking a connection request from a handover user for service type e in cell i. Since the connection requests from handover users have higher priority than the connection requests from new users, it requires that $\beta_{i,e}^{cn}\left(m_i^c\right) \leq \beta_{i,e}^{ch}\left(m_i^c\right)$ for all $i \in M^c$, and $e \in E$. Many admission control policies, including CP and FG can be mathematically modelled in the form of their corresponding policy functions.

6.3.1 Handover calls to cell

The horizontal handover rate of service type e offered to cell i from its adjacent cell j is $\lambda_{ij,e}^{cc}$. It is all the non-blocked (dropped) traffic in cell j multiply with a handover factor. So the formula for horizontal handover is given by equation 6..

$$\lambda_{ji,e}^{(cc)} = H_{ji,e}^{(cc)} \cdot \left[\lambda_{j,e}^{(cn)}\left(1 - B_{ji,e}^{(c)}\right) + \left(\sum_{x \in A_j^c} \lambda_{xj,e}^{(cc)} + \sum_{l \in W_j^c} \lambda_{lj,e}^{(wc)} + \sum_{l \in W_j^c} \lambda_{lj,e}^{(wo)} \right) \cdot \left(1 - D_{ji,e}^{(c)}\right) \right] \tag{6.6}$$

Where $B_{ji,e}^{(c)}$ and $D_{ji,e}^{(c)}$ are the new call blocking and handover dropping probabilities in cell j for traffic type e respectively.

$\lambda_{ki_s e}^{wo}$ is the rate of all handover traffic of service type e that is not accepted in WLAN k and hence is transferred to cell i,

$$\lambda_{ki_s}^{(wo)} = D_k^{(w)} \cdot \left(\lambda_{ik,e}^{(cw)} + \sum_{l \in A_k^w} \lambda_{lk,e}^{(ww)} \right) \tag{6.7}$$

$\lambda_{ki,e}^{(wc)}$ is the vertical handover rate of service type e offered to cell i from its underlying WLAN k. It is given by

$$\lambda_{ki,e}^{(wc)} = H_{ki_s}^{(wc)} \cdot \left[\lambda_{k,e}^{(wn)}\left(1 - B_{k,e}^{(w)}\right) + \left(\sum_{l \in A_k^w} \lambda_{lk,e}^{(ww)} + \sum_{j \in D_k^w} \lambda_{jk,e}^{(cw)} + \sum_{j \in D_k^w} \lambda_{jk,e}^{(cw)} \right) \cdot \left(1 - D_{k,e}^{(w)}\right) \right] \tag{6.8}$$

6.3.2 *Handover calls to WLAN*

Similarly the horizontal handover rate of service type e offered to WLAN k from its adjacent WLAN l as $\lambda_{lk,e}^{(ww)}$ is given by

$$\lambda_{lk,e}^{(ww)} = H_{lk,e}^{(ww)} \cdot \left[\lambda_{l,e}^{(wn)}\left(1 - B_{l,e}^{(w)}\right)R_{ik} + \left(\sum_{y \in A_l^w} \lambda_{yl,e}^{(ww)} R_{ik} + \sum_{i \in D_l^w} \lambda_{il,e}^{(cw)} R_{ik} + \sum_{i \in D_l^w} \lambda_{il,e}^{(co)} \right) \cdot \left(1 - D_{l,e}^{(w)}\right) \right] \tag{6.9}$$

$\lambda_{ik,e}^{wo}$ denotes the rate of all handover traffic of service type e that is not accepted in WLAN k and hence is transferred to WLAN k.

$$\tau_{ik_s}^{cw} = \left(\upsilon_{ki_s}^{wc} B_{h_{i_s}}^{w} + \sum_{j \in A_i^c} h_{ji_s}^{cc} B_{h_{i_s}}^{w} \right) R_{ik} \tag{6.10}$$

$\lambda_{ik,e}^{(cw)}$ denotes the vertical handover rate of service type e officered to WLAN k from its overlaying cell i,

$$\lambda_{ik,e}^{(cw)} = H_{ik,e}^{(cw)} \cdot \left[\lambda_{i,e}^{(cn)}\left(1 - B_{i,e}^{(c)}\right) + \left(\sum_{j \in A_i^c} \lambda_{ji,e}^{(cc)} + \sum_{l \in W_i^c} \lambda_{li,e}^{(wc)} + \sum_{l \in W_i^c} \lambda_{li,e}^{(wc)} \right) \cdot \left(1 - D_{i,e}^{(c)}\right) \right] \tag{6.11}$$

Where R_{ik} denotes the coverage factor between WLAN k and cell i (i.e., the ratio between the radio coverage area of WLAN k and the radio coverage area of cell i). Note that we always have $0 \le R_{ik} \le 1$ for all $i \in M^c$ and $k \in W_i^c$.

6.4 Balance Equations

A channel occupancy vector m_i^c is feasible if $m_{i,e}^c \ge 0$ for all $e \in E$ and (3) holds. We denote the set of all feasible m_i^c as Θ_i^c. The occupancy of cell i evolves according to a multi-dimensional birth-death process [GB98] independent of other cells. A birth event happens when a connection request to cell i from a handover or a new user is accepted. A death event happens when a user terminates its connection or leaves cell i . The multi-dimensional birth-death process has $|E|$ dimensions, where $|\cdot|$ denotes the set's cardinality. The e^{th} dimension models the channel occupancy evolution over time because of changes in the number of connections of service class e .

Let $\pi_i^c\left(m_{i,1}^c, m_{i,2}^c, \ldots, m_{i,E}^c\right)$(or simply $\pi_i^c\left(m_i^c\right)$) denote the probability of being in state $\left(m_{i,1}^c, m_{i,2}^c, \cdots, m_{i,E}^c\right)$ in the $|E|$-dimensional birth-death process corresponding to cell i .

Let $\varphi_{i_s}^c$ denote the death rate (i.e., the rate of occurance of death events) of service type e in the birth-death process corresponding to cell i . Similarly, let $\varphi_{k_s}^w$ denote the death rate of service type s in the birth-death process corresponding to WLAN k . So (6.17) and (6.18) can be derived.

$$\varphi_{i,e}^c = m_{i,e}^c\left(\mu_{i,e}^c + \upsilon_{i,e}^c\right) \tag{6.12}$$

$$\varphi_{k,e}^w = m_{k,e}^w\left(\mu_{k,e}^w + \upsilon_{k,e}^w\right) \tag{6.13}$$

6.5 QoS Metrics

In the cellular system the new call blocking probability $B_{i,e}^{(c)}$ in cell i for service type e is given by

$$B_{i,e}^{(c)} = \sum_{m_i^c \in \Theta_i^c} \pi_i^c\left(m_i^c\right)\beta_{i,e}^{cn}\left(m_i^c\right) \tag{6.14}$$

And the handover dropping probability

$$D_{i,e}^{(c)} = \sum_{m_i^c \in \Theta_i^c} \pi_i^c\left(m_i^c\right)\beta_{i,e}^{ch}\left(m_i^c\right) \tag{6.15}$$

Where $B_{i,e}^{c}$ and $D_{i,e}^{c}$ denote the probability of blocking connection requests for service e in cell i from new and handover users, respectively.

To model the capacity in IEEE802.11 WLANs, we reasonably assume that there are only packet transmissions from the access point to the users and vice versa, but not among the users. For each WLAN k, the media access is controlled either in a centralized manner using the Point Coordination Function (PCF), or in a decentralized manner using Distributed Coordination Function (DCF). In either case, the capacity constraint can be modeled as:

$$\sum_{e \in E} m_{k,e}^{w} b_e \le C_k^{w}, \qquad \forall i \in W^c \tag{6.16}$$

Where C_k^{w} is the nominal data rate in WLAN k, b_s is the required effective data rate for service $e \in E$ in BBUs, and $m_{k,e}^{w} \ge 0$ is the number of connections of service e in WLAN k. We denote $m_k^{w} = \left(m_{k,1}^{w}, m_{k,2}^{w}, \cdots, m_{k,E}^{w}\right)$ as the channel occupancy vector in WLAN k.

Consider an arbitrary cell $i \in M^c$. For each WLAN $k \in W_i^c$, admission control policies on connection requests from handover and new users for service $e \in E$ can be modeled by policy function $\beta_{k,e}^{wn}\left(m_k^{w}\right)$ and $\beta_{k,e}^{wh}\left(m_k^{w}\right)$, respectively.

A channel occupancy vector m_k^{w} is feasible if $m_{k,e}^{w} \ge 0$ for all $e \in E$ and (6.6) holds. We denote the set of all feasible m_k^{w} as Θ_k^{w}. The occupancy of WLAN k evolves according to a $|S|$-dimensional birth-death process independent of other WLANs. Let $P_k^{w}\left(m_{k,1}^{w}, m_{k,2}^{w}, \ldots, m_{k,E}^{w}\right)$(or simply $P_k^{w}\left(m_k^{w}\right)$) denote the probability of being in state $\left(m_{k,1}^{w}, m_{k,2}^{w}, \cdots, m_{k,E}^{w}\right)$ in the $|E|$-dimensional birth-death process corresponding to WLAN k. Let $B_{k,e}^{w}$ and $D_{k,e}^{w}$ denote the probability of blocking connection requests for service s in cell i from new and handover users, respectively. They can be derived as:

$$B_{k,e}^{(w)} = \sum_{m_k^w \in \Theta_k^w} \pi_k^w \left(m_k^w\right) \beta_{k,e}^{wn} \left(m_k^w\right) \tag{6.17}$$

$$D_{k,e}^{(w)} = \sum_{m_k^w \in \Theta_k^w} \pi_k^w \left(m_k^w\right) \beta_{k,e}^{wh} \left(m_k^w\right) \tag{6.18}$$

Given the policy function $\beta_{i,e}^{cn}$, $\beta_{i,e}^{ch}$, $\beta_{k,e}^{wn}$ and $\beta_{k,e}^{wh}$ and network parameters $\lambda_{i_s}^{c}$, $\lambda_{k_s}^{w}$ η_i^c, η_k^w, $\mu_{i,e}^c$, $\mu_{k,e}^w$, $\upsilon_{i,e}^c$, $\upsilon_{k,e}^w$, $H_{ij,e}^{(cc)}$, $H_{ik,e}^{(cw)}$, $H_{kl,e}^{(ww)}$, $H_{ki,e}^{(wc)}$, C_i^c, C_k^w, υ_s, b_s for all $i, j \in M^c$, all $k, l \in W_i^c$, and $s \in S$, I solve the global balance equations from the birth-death processes and obtain blocking probabilities $B_{n_{i_s}}^c$, $B_{h_{i_s}}^c$, $B_{n_{k_s}}^w$ and $B_{h_{k_s}}^w$ for all $i \in M^c$, all $k \in W_i^c$, and $s \in S$. To compute the birth rate in (6.9) and (6.10), it is needed to solve the set of fixed-point equations given by the handover rates (6.11)-(6.16). It can be accomplished by using the iterative fixed-point algorithm of repeated substitutions. Scenarios based on this model and results will be given in chapter 7.

6.6 Summary

In this chapter, I discussed the multi-rate traffic type based on the mathematical model of a cellular/WLAN interworking network given in last chapter. I first introduced the traffic and mobility models and then discussed multi-dimensional birth-death processes that are used in the analysis of traffic flow in the system. Though multi-rate traffic brings more difficulty, the model copes well.

Chapter 7 SCENARIOS AND NUMERICAL RESULTS

In this chapter, I test my analytic model against some scenarios. I use the first scenario to validate the correctness of my analytic model. The second scenario is a more realistic environment with different number of WLANs deployed in each cellular cell. My model applies to more complex scenario with an arbitrary number of neighbouring cellular cells and an arbitrary number of WLANs deployed in each cell.

7.1 Cellular/WLAN Integrated System with Symmetric Traffic

I evaluate a wireless system consisting of a cellular network with $N^c = 3$ and $N^w = 3$. For this simple scenario, only one WLAN is deployed in each cellular cell as shown in Figure 7.1. It is assumed that all cells in the cellular network have capacity $C_i^c = 30$ units of bandwidth, and all WLANs have capacity $C_k^w = 60$. Channel holding times in the cellular network have means $1/\mu_i^c$ =1 min, and channel holding times in the WLANs have means $1/\mu_k^w$ = 4 min. The coverage factor R_{jk} is set to 0.65. All the parameter are listed in Table 7.1.

Table 7.1 Parameters for the scenario of cellular/WLAN interworking with symmetric traffic

Parameter	Value
Number of cellular cell nodes N^c	3
Number of WLAN nodes N^w	3
Capacity of each cellular node C_i^c	30
Capacity of each WLAN node C_k^w	60
Channel holding time for cellular node $1/\mu_i^c$	1 min
Channel holding time for WLAN node $1/\mu_k^w$	4 min
Coverage factor R_{jk}	0.65

WLAN having a higher bandwidth than cellular network is reflected here as the network capacity as it can be seen that the capacity of a WLAN node is double the size of a cellular node. Channel holding time reflects the user mobility level. So here WLAN nodes are given a longer channel holding time because the user mobility is much lower in WLAN than in cellular network, i.e. the mobile terminals tend to stay longer in a WLAN node than in a cellular node. Coverage difference is reflected from the coverage factor which is the ration of the coverage area of a WLAN to a cellular network.

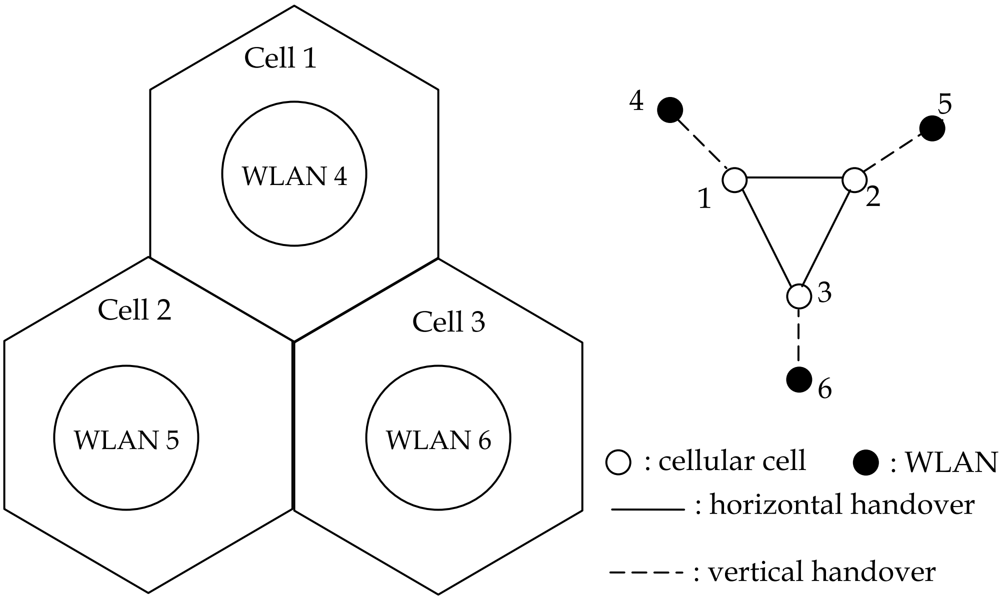


Figure 7.1 Symmetric traffic scenario deployment and network topology

From equations (6.1) and (6.2) in chapter 6, I obtain the incoming traffic rate for each cell and each WLAN as follows

$$\lambda_1^c = \lambda_1^{(cn)} + \left(\lambda_{21}^{(cc)} + \lambda_{31}^{(cc)}\right) + \lambda_{41}^{(wc)} + \lambda_{14}^{(cw)} D_4^{(w)} \tag{7.1}$$

$$\lambda_2^c = \lambda_2^{(cn)} + \left(\lambda_{12}^{(cc)} + \lambda_{32}^{(cc)}\right) + \lambda_{52}^{(wc)} + \lambda_{25}^{(cw)} D_5^{(w)} \tag{7.2}$$

$$\lambda_3^c = \lambda_3^{(cn)} + \left(\lambda_{13}^{(cc)} + \lambda_{23}^{(cc)}\right) + \lambda_{63}^{(wc)} + \lambda_{36}^{(cw)} D_6^{(w)} \tag{7.3}$$

$$\lambda_4^w = \lambda_4^{(wn)} + \lambda_{14}^{(cw)} + \left(\lambda_{41}^{(wc)} + \lambda_{21}^{(cc)} + \lambda_{31}^{(cc)}\right) D_1^{(c)} \gamma_{14} \tag{7.4}$$

$$\lambda_5^{w} = \lambda_5^{(wn)} + \lambda_{25}^{(cw)} + \left(\lambda_{52}^{(wc)} + \lambda_{12}^{(cc)} + \lambda_{32}^{(cc)}\right) D_2^{(c)} \gamma_{25} \tag{7.5}$$

$$\lambda_6^{w} = \lambda_6^{(wn)} + \lambda_{36}^{(cw)} + \left(\lambda_{63}^{(wc)} + \lambda_{13}^{(cc)} + \lambda_{23}^{(cc)}\right) D_3^{(c)} \gamma_{36} \tag{7.6}$$

7.1.1 Handover Rate Equations

Horizontal handover rate equations among the cells are derived from equations (6.3)-(6.6) as below. There are no horizontal handovers between WLANs because for each WLAN there is no neighbouring WLAN around it, so only vertical handover to the overlaid cell can happen.

$$\lambda_{12}^{(cc)} = H_{12}^{(cc)} \cdot \left\{\lambda_1^{(cn)} \cdot \left(1 - B_1^{(c)}\right) + \left[\left(\lambda_{21}^{(cc)} + \lambda_{31}^{(cc)}\right) + \lambda_{41}^{(wc)} + \lambda_{14}^{(cw)} B_4^{(w)}\right] \cdot \left(1 - D_1^{(c)}\right)\right\} \tag{7.7}$$

$$\lambda_{21}^{(cc)} = H_{21}^{(cc)} \cdot \left\{\lambda_2^{(cn)} \cdot \left(1 - B_2^{(c)}\right) + \left[\left(\lambda_{12}^{(cc)} + \lambda_{32}^{(cc)}\right) + \lambda_{52}^{(wc)} + \lambda_{25}^{(cw)} B_5^{(w)}\right] \cdot \left(1 - D_2^{(c)}\right)\right\} \tag{7.8}$$

$$\lambda_{13}^{(cc)} = H_{13}^{(cc)} \cdot \left\{\lambda_1^{(cn)} \cdot \left(1 - B_1^{(c)}\right) + \left[\left(\lambda_{21}^{(cc)} + \lambda_{31}^{(cc)}\right) + \lambda_{41}^{(wc)} + \lambda_{14}^{(cw)} B_4^{(w)}\right] \cdot \left(1 - D_1^{(c)}\right)\right\} \tag{7.9}$$

$$\lambda_{31}^{(cc)} = H_{31}^{(cc)} \cdot \left\{\lambda_3^{(cn)} \cdot \left(1 - B_3^{(c)}\right) + \left[\left(\lambda_{13}^{(cc)} + \lambda_{23}^{(cc)}\right) + \lambda_{63}^{(wc)} + \lambda_{36}^{(cw)} B_6^{(w)}\right] \cdot \left(1 - D_3^{(c)}\right)\right\} \tag{7.10}$$

$$\lambda_{23}^{(cc)} = H_{23}^{(cc)} \cdot \left\{\lambda_2^{(cn)} \cdot \left(1 - B_2^{(c)}\right) + \left[\left(\lambda_{12}^{(cc)} + \lambda_{32}^{(cc)}\right) + \lambda_{52}^{(wc)} + \lambda_{25}^{(cw)} B_5^{(w)}\right] \cdot \left(1 - D_2^{(c)}\right)\right\} \tag{7.11}$$

$$\lambda_{32}^{(cc)} = H_{32}^{(cc)} \cdot \left\{\lambda_3^{(cn)} \cdot \left(1 - B_3^{(c)}\right) + \left[\left(\lambda_{13}^{(cc)} + \lambda_{23}^{(cc)}\right) + \lambda_{63}^{(wc)} + \lambda_{36}^{(cw)} B_6^{(w)}\right] \cdot \left(1 - D_3^{(c)}\right)\right\} \tag{7.12}$$

Vertical handover traffic consists of two parts. One is the upward vertical handover from WLAN cells to their overlay cellular cells, the other is the downward handover traffic from cellular cells to WLAN cells. The vertical handover rate equations are given as follows.

Upward vertical handover traffic:

$$\lambda_{41}^{(wc)} = H_{41}^{(wc)} \cdot \left\{\lambda_{4}^{(wn)} \cdot \left(1 - B_{4}^{(w)}\right) + \left[\lambda_{14}^{(cw)} + \left(\lambda_{41}^{(wc)} + \lambda_{21}^{(cc)} + \lambda_{31}^{(cc)}\right)\gamma_{14} B_{1}^{(c)}\right] \cdot \left(1 - D_{4}^{(w)}\right)\right\} \tag{7.13}$$

$$\lambda_{52}^{(wc)} = H_{52}^{(wc)} \cdot \left\{\lambda_{5}^{(wn)} \cdot \left(1 - B_{5}^{(w)}\right) + \left[\lambda_{25}^{(cw)} + \left(\lambda_{52}^{(wc)} + \lambda_{12}^{(cc)} + \lambda_{32}^{(cc)}\right)\gamma_{25} B_{2}^{(c)}\right] \cdot \left(1 - D_{5}^{(w)}\right)\right\} \tag{7.14}$$

$$\lambda_{63}^{(wc)} = H_{63}^{(wc)} \cdot \left\{\lambda_{6}^{(wn)} \cdot \left(1 - B_{6}^{(w)}\right) + \left[\lambda_{36}^{(cw)} + \left(\lambda_{63}^{(wc)} + \lambda_{13}^{(cc)} + \lambda_{23}^{(cc)}\right)\gamma_{36} B_{3}^{(c)}\right] \cdot \left(1 - D_{6}^{(w)}\right)\right\} \tag{7.15}$$

Downward vertical handover traffic:

$$\lambda_{14}^{(cw)} = H_{14}^{(cw)} \cdot \left\{\lambda_{1}^{(cn)} \cdot \left(1 - B_{1}^{(c)}\right) + \left[\left(\lambda_{21}^{(cc)} + \lambda_{31}^{(cc)}\right) + \lambda_{41}^{(wc)} + \lambda_{14}^{(cw)}\right] \cdot \left(1 - D_{1}^{(c)}\right)\right\} \cdot \gamma_{14} \tag{7.16}$$

$$\lambda_{25}^{(cw)} = H_{25}^{(cw)} \cdot \left\{\lambda_{2}^{(cn)} \cdot \left(1 - B_{2}^{(c)}\right) + \left[\left(\lambda_{12}^{(cc)} + \lambda_{32}^{(cc)}\right) + \lambda_{52}^{(wc)} + \lambda_{25}^{(cw)}\right] \cdot \left(1 - D_{2}^{(c)}\right)\right\} \cdot \gamma_{25} \tag{7.17}$$

$$\lambda_{36}^{(cw)} = H_{36}^{(cw)} \cdot \left\{\lambda_{3}^{(cn)} \cdot \left(1 - B_{3}^{(c)}\right) + \left[\left(\lambda_{13}^{(cc)} + \lambda_{23}^{(cc)}\right) + \lambda_{63}^{(wc)} + \lambda_{36}^{(cw)}\right] \cdot \left(1 - D_{3}^{(c)}\right)\right\} \cdot \gamma_{36} \tag{7.18}$$

7.1.2 Results and Analysis

From the balance equations, we can recursively calculate the steady-state probabilities, and then calculate the new call blocking probabilities and the handover call dropping probabilities.

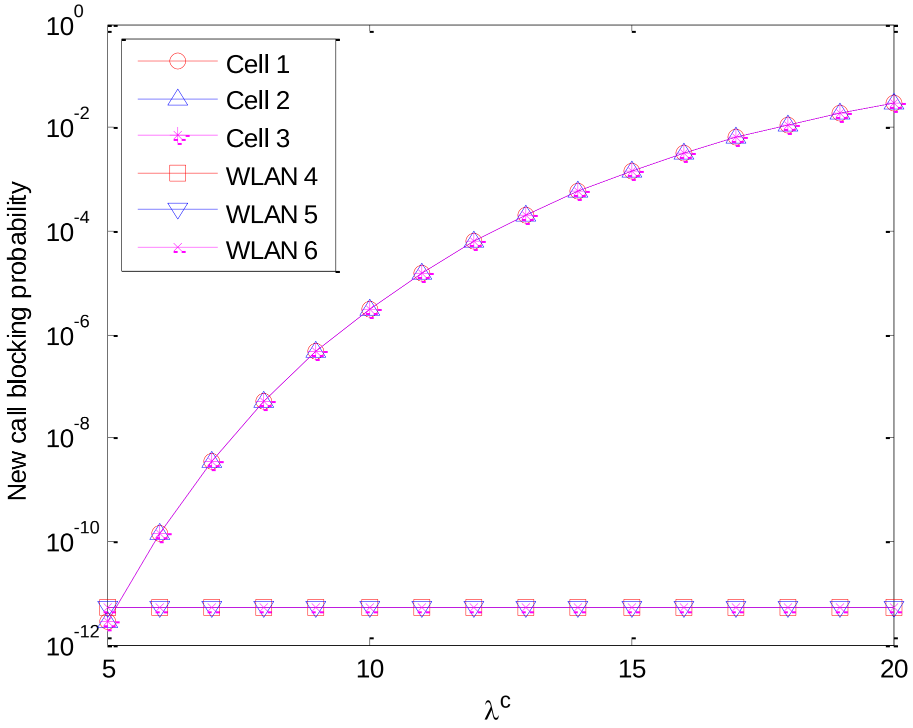


Figure 7.2 New call blocking probabilities in each cell and WLAN

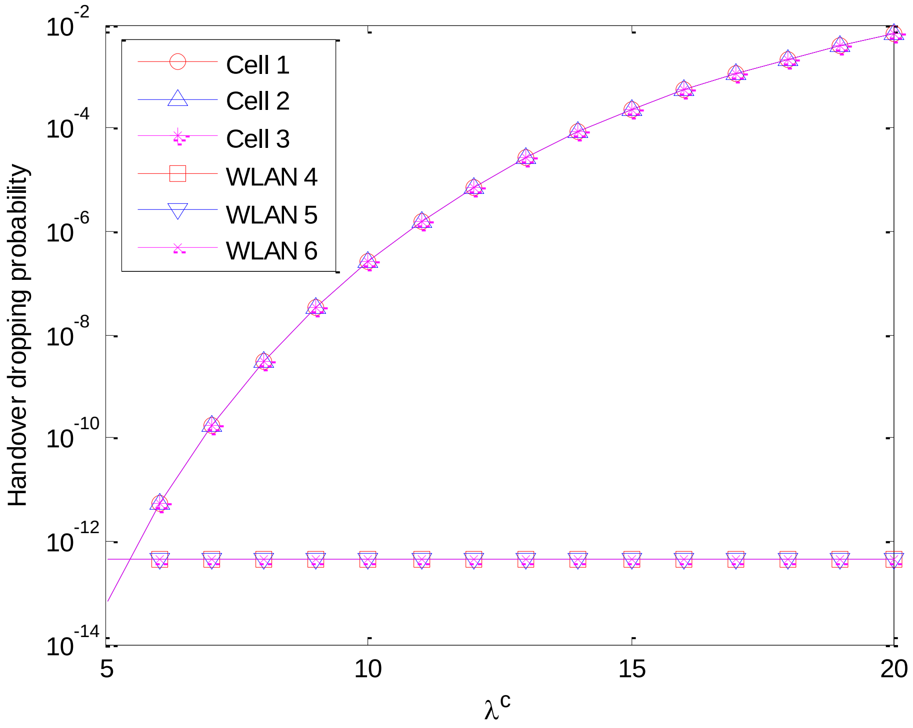


Figure 7.3 Handover blocking probabilities in each cell and WLAN

The results validate the correctness of my analytical model. Because the traffic is symmetric, the blocking rate and dropping rate for each cell and each WLAN are the same.

7.2 Cellular/WLAN Integrated System with Asymmetric Traffic

In the second scenario, I still evaluate a wireless system consisting of a cellular network with $N^c = 3$ and $N^w = 3$, but this time the layout of the WLANs is different from Scenario 1. The parameters are given in Table 7.2. There are two WLANs in cell 1 numbered 4 and 5, one WLAN in cell 2, numbered 6, and no WLAN in cell 3. The network deployment and topology is shown in figure 7.4.

Table 7.2 Parameters for the scenario of cellular/WLAN interworking with asymmetric traffic

Parameter	Value
Number of cellular cell nodes N^c	3
Number of WLAN nodes N^w	3
Capacity of each cellular node C_i^c	30
Capacity of each WLAN node C_k^w	60
Channel holding time for cellular node $1/\mu_i^c$	1 min
Channel holding time for WLAN node $1/\mu_k^w$	4 min
Coverage factor R_{jk}	0.65

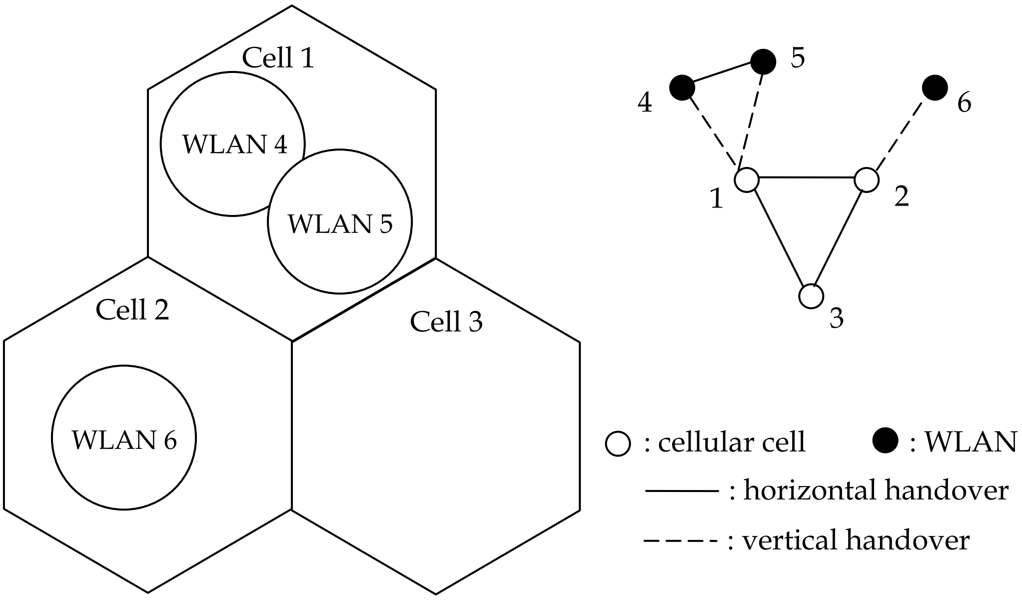


Figure 7.4 Asymmetric traffic scenario deployment and network topology

From the formula in chapter 6, we can obtain the incoming traffic rate for each cell and each WLAN is as follows

$$\lambda_1^c = \lambda_1^{(cn)} + \left(\lambda_{21}^{(cc)} + \lambda_{31}^{(cc)}\right) + \left(\lambda_{41}^{(wc)} + \lambda_{51}^{(wc)}\right) + \left[\left(\lambda_{14}^{(cw)} + \lambda_{54}^{(ww)}\right)D_4^{(w)} + \left(\lambda_{15}^{(cw)} + \lambda_{45}^{(ww)}\right)D_5^{(w)}\right] \quad (7.19)$$

$$\lambda_2^c = \lambda_2^{(cn)} + \left(\lambda_{12}^{(cc)} + \lambda_{32}^{(cc)}\right) + \lambda_{62}^{(wc)} + \lambda_{26}^{(cw)} D_6^{(w)} \quad (7.20)$$

$$\lambda_3^c = \lambda_3^{(cn)} + \left(\lambda_{13}^{(cc)} + \lambda_{23}^{(cc)}\right) + 0 + 0 \quad (7.21)$$

$$\lambda_4^w = \lambda_4^{(wn)} + \lambda_{54}^{(ww)} + \lambda_{14}^{(cw)} + \left(\lambda_{41}^{(wc)} + \lambda_{21}^{(cc)} + \lambda_{31}^{(cc)}\right) D_1^{(c)} \gamma_{14} \quad (7.22)$$

$$\lambda_5^w = \lambda_5^{(wn)} + \lambda_{45}^{(ww)} + \lambda_{15}^{(cw)} + \left(\lambda_{51}^{(wc)} + \lambda_{21}^{(cc)} + \lambda_{31}^{(cc)}\right) D_1^{(c)} \gamma_{15} \quad (7.23)$$

$$\lambda_6^w = \lambda_6^{(wn)} + 0 + \lambda_{26}^{(cw)} + \left(\lambda_{62}^{(wc)} + \lambda_{12}^{(cc)} + \lambda_{32}^{(cc)}\right) D_2^{(c)} \gamma_{36} \quad (7.24)$$

Horizontal handover equations can be derived from

Cell to cell

$$\lambda_{21}^{(cc)} = H_{21}^{(cc)} \cdot \left\{\lambda_{2}^{(cn)} \cdot \left(1 - B_{2}^{(c)}\right) + \left[\left(\lambda_{12}^{(cc)} + \lambda_{32}^{(cc)}\right) + \lambda_{62}^{(wc)} + \lambda_{26}^{(cw)} B_{6}^{(w)}\right] \cdot \left(1 - D_{2}^{(c)}\right)\right\} \tag{7.25}$$

$$\lambda_{31}^{(cc)} = H_{31}^{(cc)} \cdot \left\{\lambda_{3}^{(cn)} \cdot \left(1 - B_{3}^{(c)}\right) + \left[\left(\lambda_{13}^{(cc)} + \lambda_{23}^{(cc)}\right) + 0 + 0\right] \cdot \left(1 - D_{3}^{(c)}\right)\right\} \tag{7.26}$$

$$\begin{aligned} \lambda_{12}^{(cc)} = H_{12}^{(cc)} \cdot \{ \lambda_{1}^{(cn)} \cdot \left(1 - B_{1}^{(c)}\right) + \\ \left[\left(\lambda_{21}^{(cc)} + \lambda_{31}^{(cc)}\right) + \left(\lambda_{41}^{(wc)} + \lambda_{51}^{(wc)}\right) + \left(\lambda_{14}^{(cw)} B_{4}^{(w)} + \lambda_{54}^{(ww)} B_{4}^{(w)} + \lambda_{15}^{(cw)} B_{5}^{(w)} + \lambda_{45}^{(ww)} B_{5}^{(w)}\right)\right] \cdot \left(1 - D_{1}^{(c)}\right) \} \end{aligned} \tag{7.27}$$

$$\lambda_{32}^{(cc)} = H_{32}^{(cc)} \cdot \left\{\lambda_{3}^{(cn)} \cdot \left(1 - B_{3}^{(c)}\right) + \left[\left(\lambda_{13}^{(cc)} + \lambda_{23}^{(cc)}\right) + 0 + 0\right] \cdot \left(1 - D_{3}^{(c)}\right)\right\} \tag{7.28}$$

$$\begin{aligned} \lambda_{13}^{(cc)} = H_{13}^{(cc)} \cdot \{ \lambda_{1}^{(cn)} \cdot \left(1 - B_{1}^{(c)}\right) + \\ \left[\left(\lambda_{21}^{(cc)} + \lambda_{31}^{(cc)}\right) + \left(\lambda_{41}^{(wc)} + \lambda_{51}^{(wc)}\right) + \left(\lambda_{14}^{(cw)} B_{4}^{(w)} + \lambda_{54}^{(ww)} B_{4}^{(w)} + \lambda_{15}^{(cw)} B_{5}^{(w)} + \lambda_{45}^{(ww)} B_{5}^{(w)}\right)\right] \cdot \left(1 - D_{1}^{(c)}\right) \} \end{aligned} \tag{7.29}$$

$$\lambda_{23}^{(cc)} = H_{23}^{(cc)} \cdot \left\{\lambda_{2}^{(cn)} \cdot \left(1 - B_{2}^{(c)}\right) + \left[\left(\lambda_{12}^{(cc)} + \lambda_{32}^{(cc)}\right) + \lambda_{62}^{(wc)} + \lambda_{26}^{(cw)} B_{5}^{(w)}\right] \cdot \left(1 - D_{2}^{(c)}\right)\right\} \tag{7.30}$$

WLAN to WLAN

$$\lambda_{45}^{(ww)} = H_{45}^{(ww)} \cdot \left\{\lambda_{4}^{(wn)} \cdot \left(1 - B_{4}^{(w)}\right) + \left[\lambda_{54}^{(ww)} + \lambda_{14}^{(cw)} + \left(\lambda_{41}^{(wc)} + \lambda_{21}^{(cc)} + \lambda_{31}^{(cc)}\right)\gamma_{14} B_{1}^{(c)}\right] \cdot \left(1 - D_{4}^{(w)}\right)\right\} \tag{7.31}$$

$$\lambda_{54}^{(ww)} = H_{54}^{(ww)} \cdot \left\{\lambda_{5}^{(wn)} \cdot \left(1 - B_{5}^{(w)}\right) + \left[\lambda_{45}^{(ww)} + \lambda_{15}^{(cw)} + \left(\lambda_{51}^{(wc)} + \lambda_{21}^{(cc)} + \lambda_{31}^{(cc)}\right)\gamma_{15} B_{1}^{(c)}\right] \cdot \left(1 - D_{5}^{(w)}\right)\right\} \tag{7.32}$$

Vertical handover traffic flows have the upward part flowing from WLANs to cellular cells and downward part flowing from cellular cells to WLANs.

Upward:

$$\lambda_{41}^{(wc)} = H_{41}^{(wc)} \cdot \left\{\lambda_{4}^{(wn)} \cdot \left(1 - B_{4}^{(w)}\right) + \left[\lambda_{54}^{(ww)} + \lambda_{14}^{(cw)} + \left(\lambda_{41}^{(wc)} + \lambda_{21}^{(cc)} + \lambda_{31}^{(cc)}\right)\gamma_{14} B_{1}^{(c)}\right] \cdot \left(1 - D_{4}^{(w)}\right)\right\} \tag{7.33}$$

$$\lambda_{51}^{(wc)} = H_{51}^{(wc)} \cdot \left\{\lambda_{5}^{(wn)} \cdot \left(1 - B_{5}^{(w)}\right) + \left[\lambda_{45}^{(ww)} + \lambda_{15}^{(cw)} + \left(\lambda_{51}^{(wc)} + \lambda_{21}^{(cc)} + \lambda_{31}^{(cc)}\right)\gamma_{15} B_{1}^{(c)}\right] \cdot \left(1 - D_{5}^{(w)}\right)\right\} \tag{7.34}$$

$$\lambda_{62}^{(wc)} = H_{62}^{(wc)} \cdot \left\{\lambda_{6}^{(wn)} \cdot \left(1 - B_{6}^{(w)}\right) + \left[0 + \lambda_{26}^{(cw)} + \left(\lambda_{62}^{(wc)} + \lambda_{12}^{(cc)} + \lambda_{32}^{(cc)}\right)\gamma_{26} B_{2}^{(c)}\right] \cdot \left(1 - D_{6}^{(w)}\right)\right\} \tag{7.35}$$

Downward:

$$\begin{aligned} \lambda_{14}^{(cw)} &= H_{14}^{(cw)} \cdot \{\lambda_{1}^{(cn)} \cdot \left(1 - B_{1}^{(c)}\right)\gamma_{14} + \\ &\left[\left(\lambda_{21}^{(cc)} + \lambda_{31}^{(cc)}\right)\gamma_{14} + \left(\lambda_{41}^{(wc)} + \lambda_{51}^{(wc)}\right)\gamma_{14} + \left(\lambda_{14}^{(cw)} B_{4}^{(w)} + \lambda_{54}^{(ww)} B_{4}^{(w)} + \lambda_{15}^{(cw)} B_{5}^{(w)} + \lambda_{45}^{(ww)} B_{5}^{(w)}\right)\right] \cdot \left(1 - D_{1}^{(c)}\right)\} \end{aligned} \tag{7.36}$$

$$\begin{aligned} \lambda_{14}^{(cw)} &= H_{14}^{(cw)} \cdot \{\lambda_{1}^{(cn)} \cdot \left(1 - B_{1}^{(c)}\right)\gamma_{14} + \\ &\left[\left(\lambda_{21}^{(cc)} + \lambda_{31}^{(cc)}\right)\gamma_{14} + \left(\lambda_{41}^{(wc)} + \lambda_{51}^{(wc)}\right)\gamma_{14} + \left(\lambda_{14}^{(cw)} B_{4}^{(w)} + \lambda_{54}^{(ww)} B_{4}^{(w)} + \lambda_{15}^{(cw)} B_{5}^{(w)} + \lambda_{45}^{(ww)} B_{5}^{(w)}\right)\right] \cdot \left(1 - D_{1}^{(c)}\right)\} \end{aligned} \tag{7.37}$$

$$\begin{aligned} \lambda_{14}^{(cw)} &= H_{14}^{(cw)} \cdot \{\lambda_{1}^{(cn)} \cdot \left(1 - B_{1}^{(c)}\right)\gamma_{14} + \\ &\left[\left(\lambda_{21}^{(cc)} + \lambda_{31}^{(cc)}\right)\gamma_{14} + \left(\lambda_{41}^{(wc)} + \lambda_{51}^{(wc)}\right)\gamma_{14} + \left(\lambda_{14}^{(cw)} B_{4}^{(w)} + \lambda_{54}^{(ww)} B_{4}^{(w)} + \lambda_{15}^{(cw)} B_{5}^{(w)} + \lambda_{45}^{(ww)} B_{5}^{(w)}\right)\right] \cdot \left(1 - D_{1}^{(c)}\right)\} \end{aligned} \tag{7.38}$$

Fig. 7.5 and Fig. 7.6 show the call blocking probabilities and handover dropping probabilities for each cellular cell and WLAN node in the interworking system when the new call arrival rate of cellular cell $\lambda_i^{(cn)}$ is increased from 5 to 20 calls per minute, and the $\lambda_k^{(wn)}$ is fixed to 5 calls per minute. Due to the distribution of the nodes being asymmetric the performance of each node is different. Except for the new traffic, both cell 1 and cell2 have overlay WLANs inside which bring extra handover traffic, so the call blocking and dropping probabilities are much higher than in cell 3 where there is no overlay WLAN. Also there are two WLANs inside cell 1 and one WLAN inside cell 2, so traffic in cell 1 is higher than in cell 2, thus the blocking and dropping probabilities are a little higher. Because of the local symmetric position of WLAN node 4 and 5, they have the same blocking and dropping probability pattern, which is to be expected.

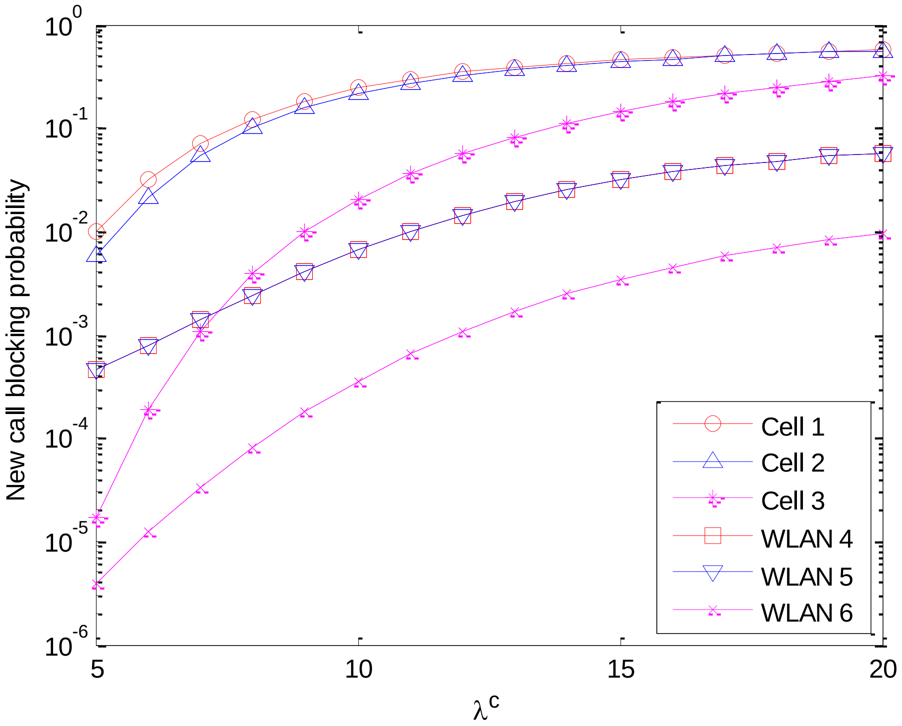


Figure 7.5 New call blocking probabilities in each cell and WLAN

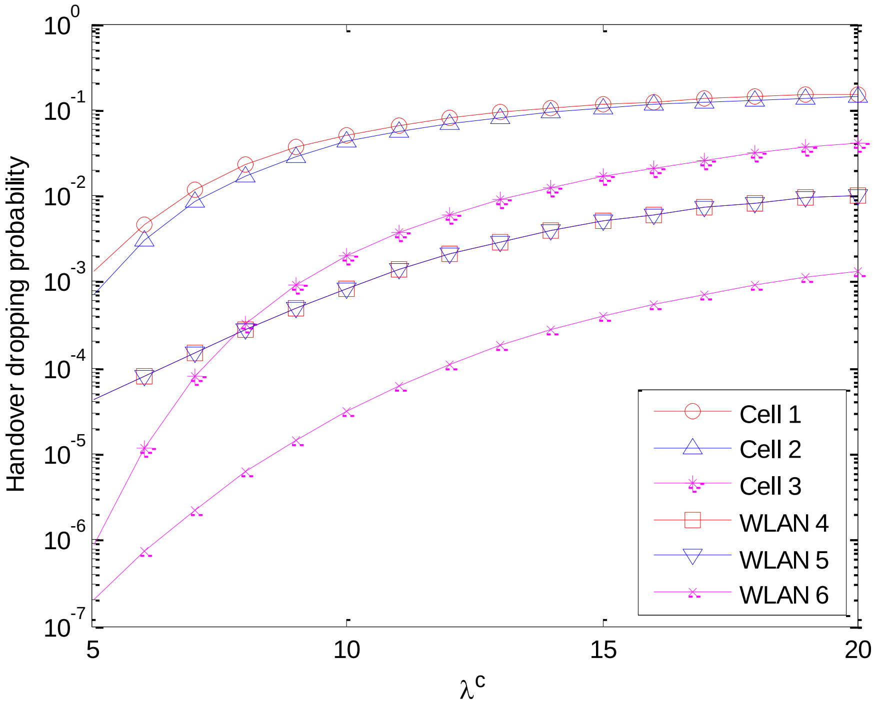


Figure 7.6 Handover blocking probabilities in each cell and WLAN

I then add the new call blocking probabilities and handover call dropping probabilities of all the cells and WLANs together, do the normalization, and obtain Fig 7.7 and Fig 7.8 with different admission policies including no admission control, cut off admission control policy and fractional guarded channel policy.

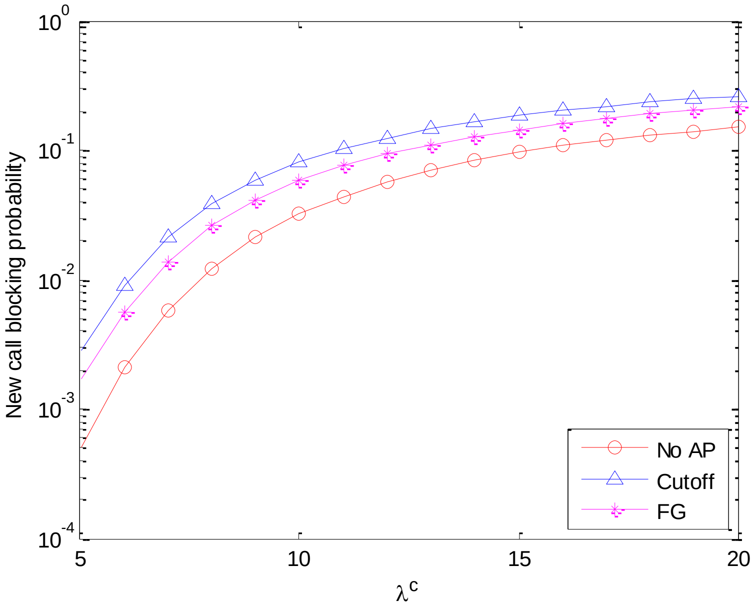


Figure 7.7 New call blocking probabilities of the system

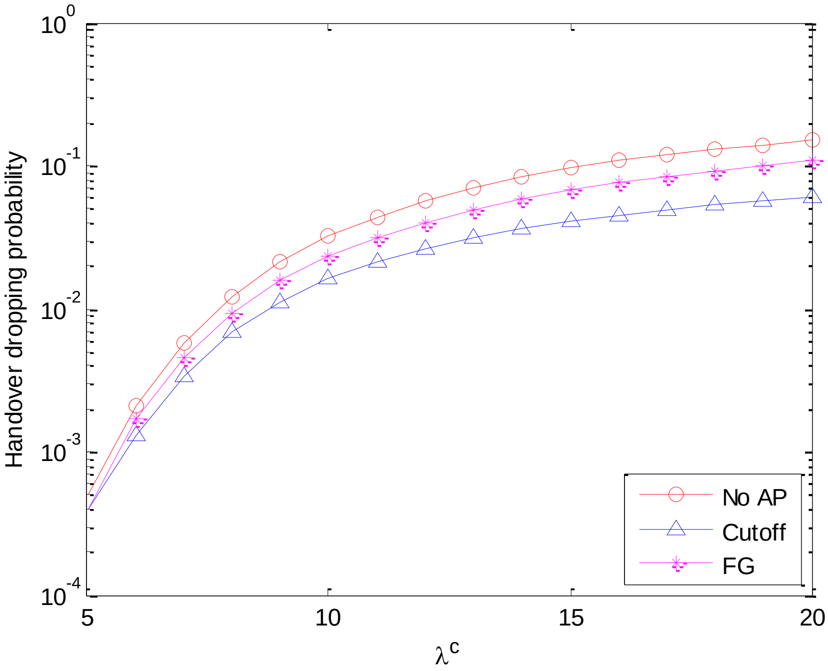


Figure 7.8 Handover call dropping of the system

It can be observed that without any admission policy, i.e. no admission control, the system has the best call blocking performance but worst handover dropping performance. When the cut off admission control policy is applied, the handover dropping performance is the best but it is the result of sacrifice of the call blocking performance. Fractional guarded channel policy has a mediocre performance on both call blocking and handover dropping performance.

I also changed both the new arrival rates in cellular cells and WLANs and obtained the 3D plotting of the blocking and dropping probabilities.

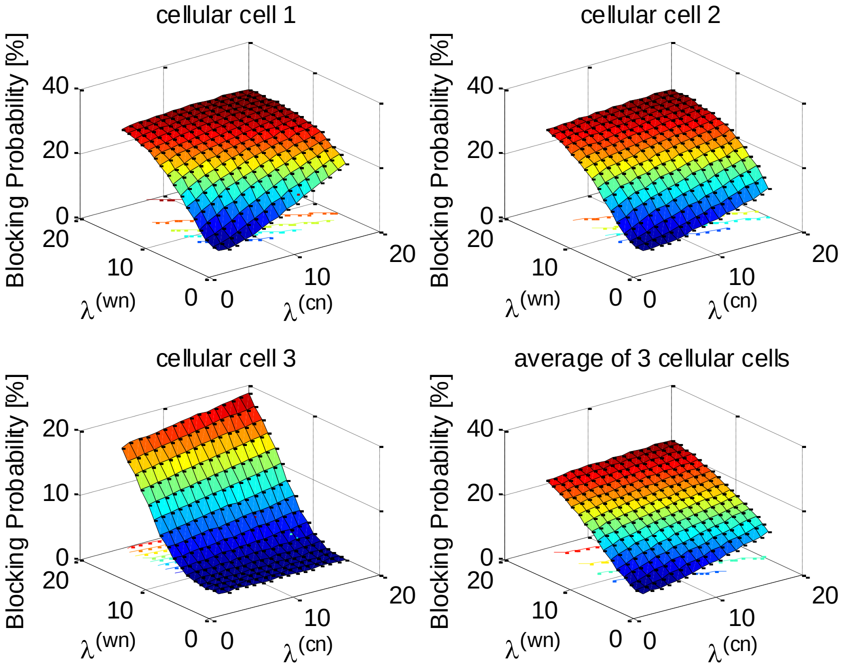


Figure 7.9 Blocking probabilities of cells

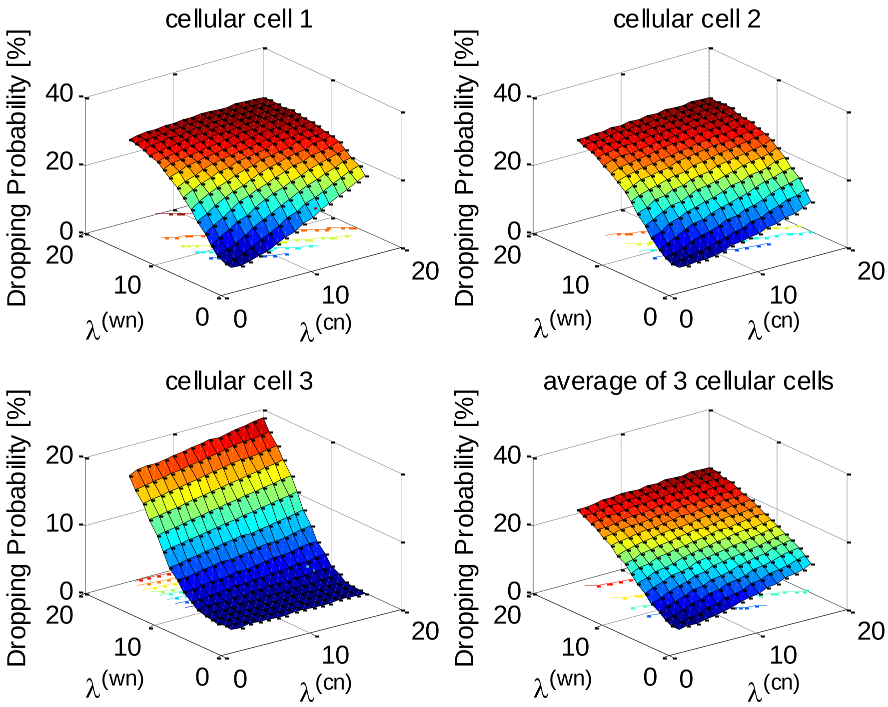


Figure 7.10 Dropping probabilities of cells

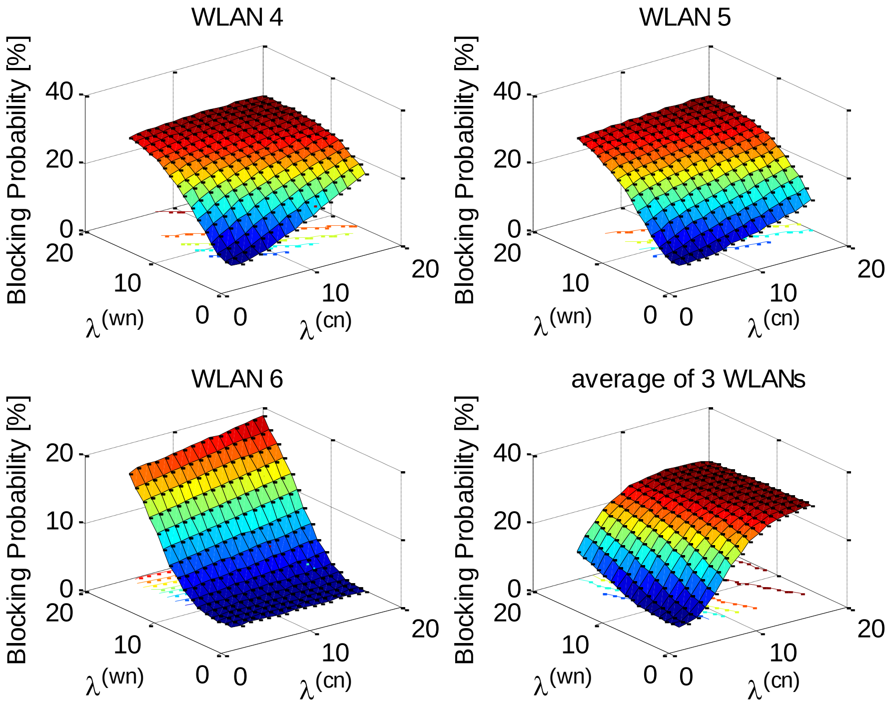


Figure 7.11 Blocking probabilities of WLANs

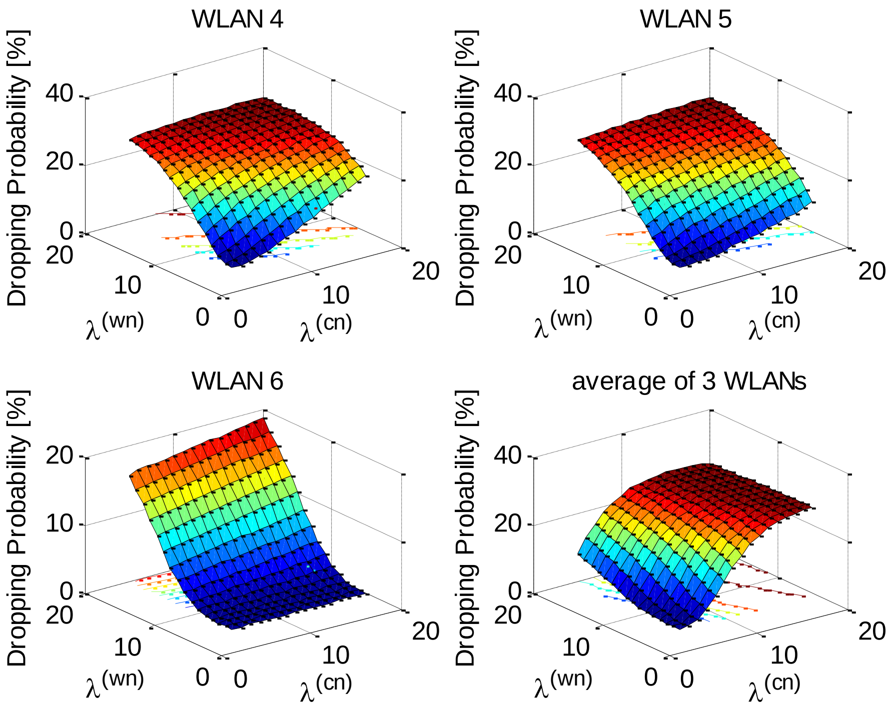


Figure 7.12 Dropping probabilities of WLANs

Assume one type arrival rate is constant, and visually track the increase in blocking probability as the arrival rate of the other type of traffic increases.

7.3 Cellular/WLAN Integrated System with Multi-Rate Traffic

In this section a scenario of a cellular/WLAN interworking system consisting of 3 cellular cells and 6 overlay WLANs with two types of traffic (I and II) is evaluated. The network topology is derived from the network deployment as shown in Fig 6.13 using the method introduced in chapter 4.

Table 7.3 Parameters for the scenario of cellular/WLAN interworking with asymmetric traffic

Parameter	Value
Number of cellular cell nodes N^c	3
Number of WLAN nodes N^w	6
Capacity of each cellular node C_i^c	30
Capacity of each WLAN node C_k^w	60
QoS provision for traffic type I b_I	1
QoS provision for traffic type I b_{II}	2
Channel holding time for cellular node $1/\mu_i^c$	1 min
Channel holding time for WLAN node $1/\mu_k^w$	4 min
Coverage factor R_{jk}	0.5

I assume that all cells in the cellular network have capacity C_i^c =30 units of bandwidth, and all WLANs have capacity C_k^w =60 units of bandwidth. QoS provisioning requires that $b_I = 1$ BBU and $b_{II} = 2$ BBU. The mean channel holding time in the cellular network is 1 min, and the mean channel holding time in the WLANs is 4 min. The coverage factor γ_{jk} is 0.5. The mobility of customers in the cellular network is $T_i^{(c)}$=0.4, and the mobility in the WLAN is $T_k^{(w)}$=0.4. These values define a mobility level of 60% (i.e., 60% of customers perform handovers).

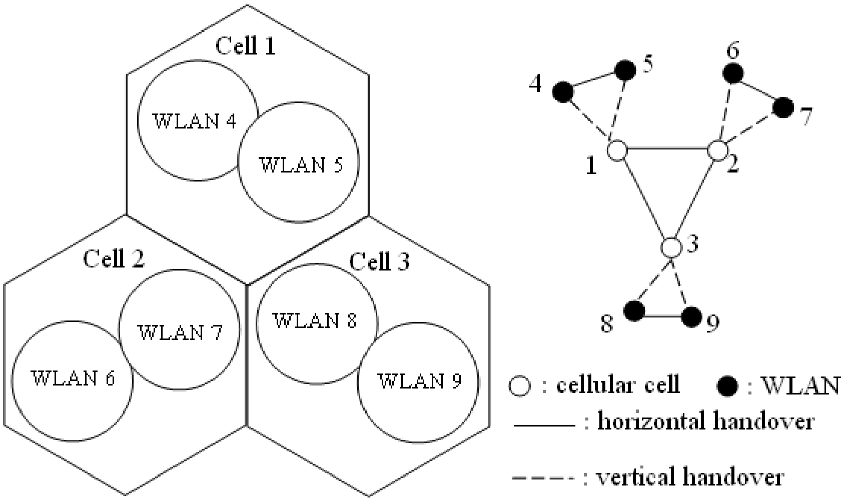


Figure 7.13 Multi-Rate traffic scenario deployment and network topology

Fig. 7.14 and 7.15 show the call blocking probabilities and handover dropping probabilities for the cellular cell nodes in the integrated system when the total new call arrival rate λ is increased from 5 to 10 calls per minute. It is divided in half between the calls that go to the cellular cell with arrival rate as $\lambda_i^{(cn)}$ and the calls that go to a WLAN with arrival rate as $\lambda_k^{(wn)}$. It consists of 75% of type I traffic and 25 % of type II traffic.

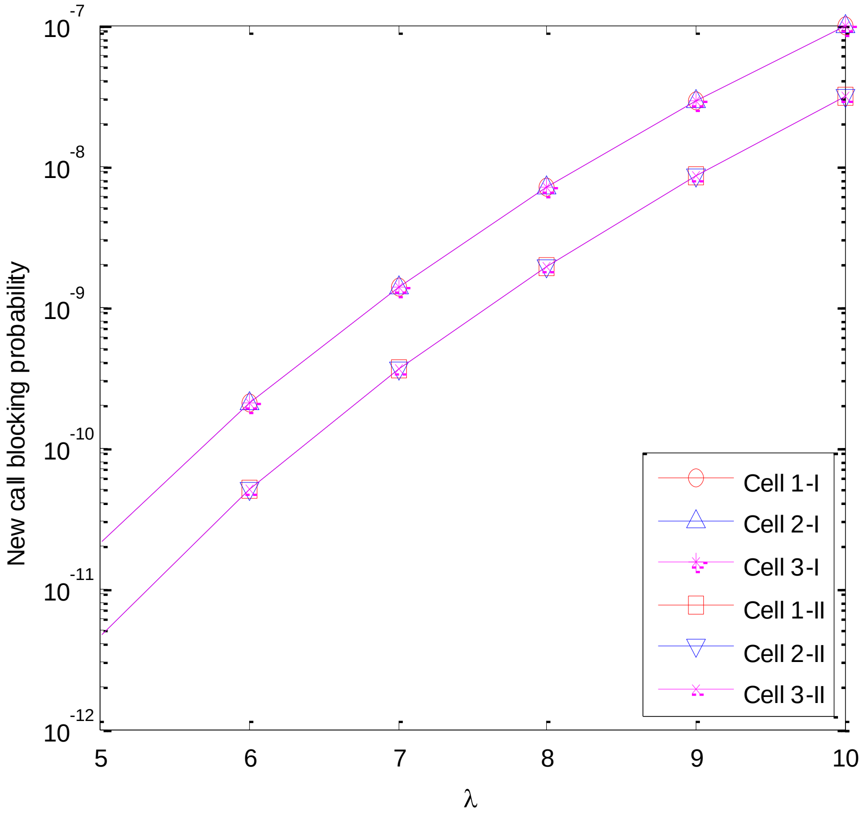


Figure 7.14 Call blocking probabilities for cellular cells

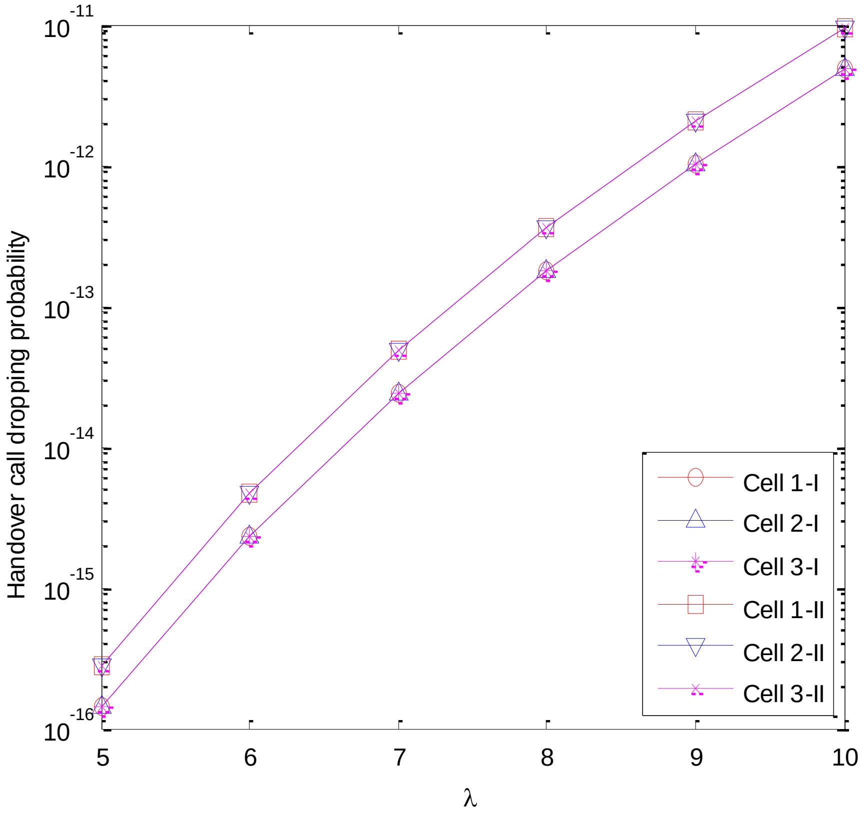


Figure 7.15 Handover dropping probabilities for cellular cells

For the same type of traffic, it can be observed that the cellular cell 1, 2 and 3 have the same blocking and dropping probability pattern as expected due to the symmetric structure of the network.

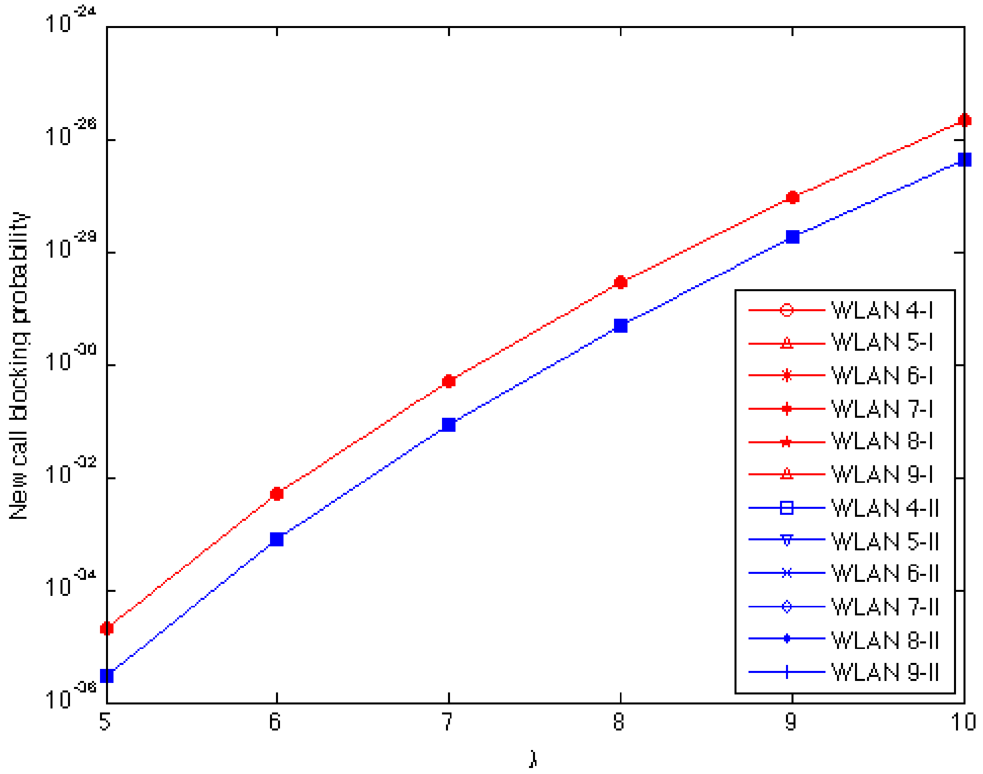


Figure 7.16 Call blocking probabilities for WLANs

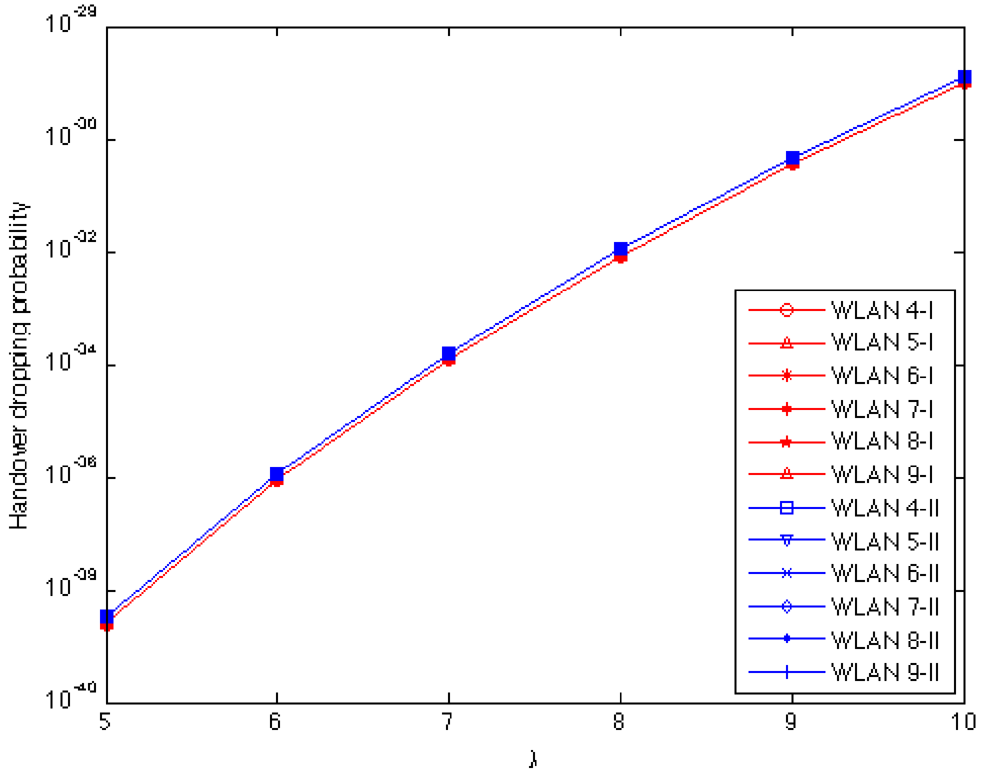


Figure 7.17 Handover dropping probabilities for WLANs

Similarly it can also be observed that for the same type of traffic the WLAN 4, 5, 6, 7, 8 and 9 have the same blocking and dropping probability pattern as expected due to the symmetric structure of the network.

I also calculated the new call blocking probabilities and handover call dropping probabilities of all the cells and WLANs with different admission policies including no admission control, cut off admission control policy and fractional guarded channel policy as shown in Figure 7.18, 7.19, 7.20 and 7.21 below.

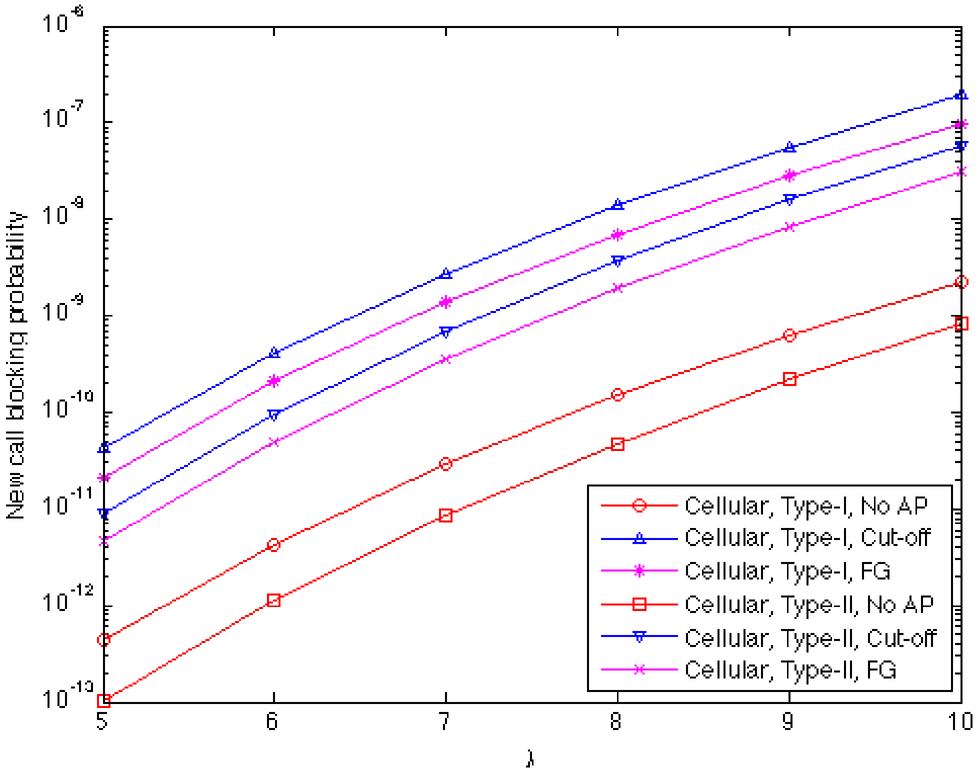


Figure 7.18 New call blocking probabilities for WLANs with different call admission policy

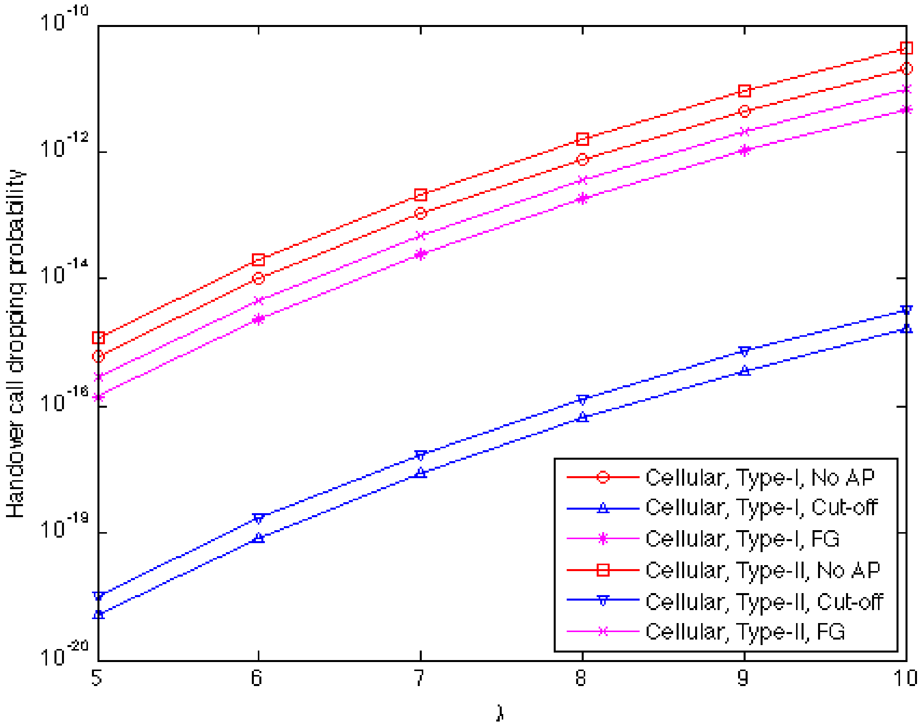


Figure 7.19 Handover dropping probabilities for cellular cells with different call admission policy

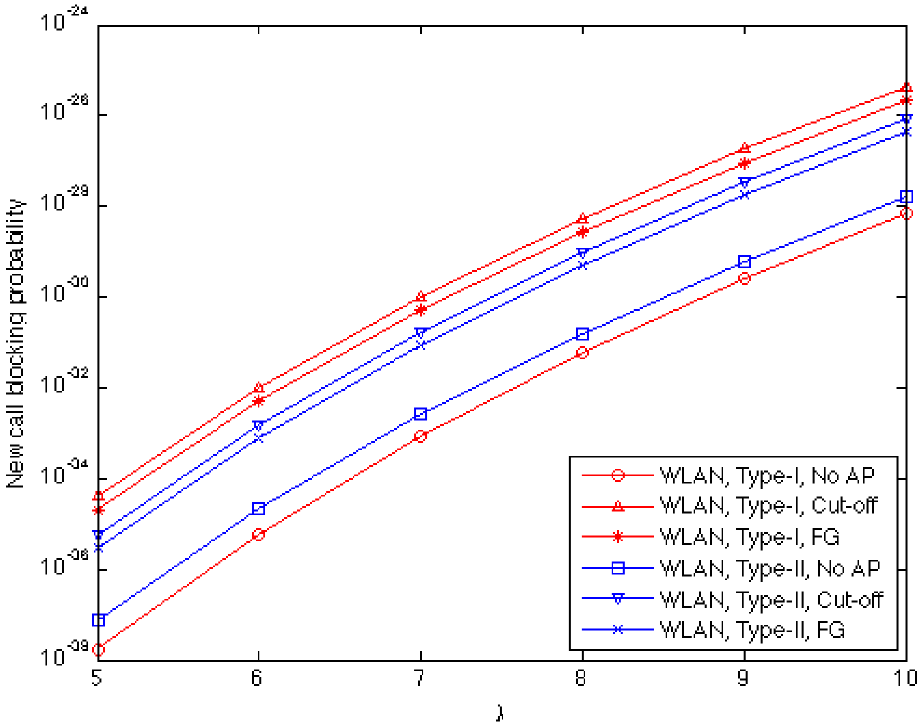


Figure 7.20 New call blocking probabilities for WLANs with different call admission policy

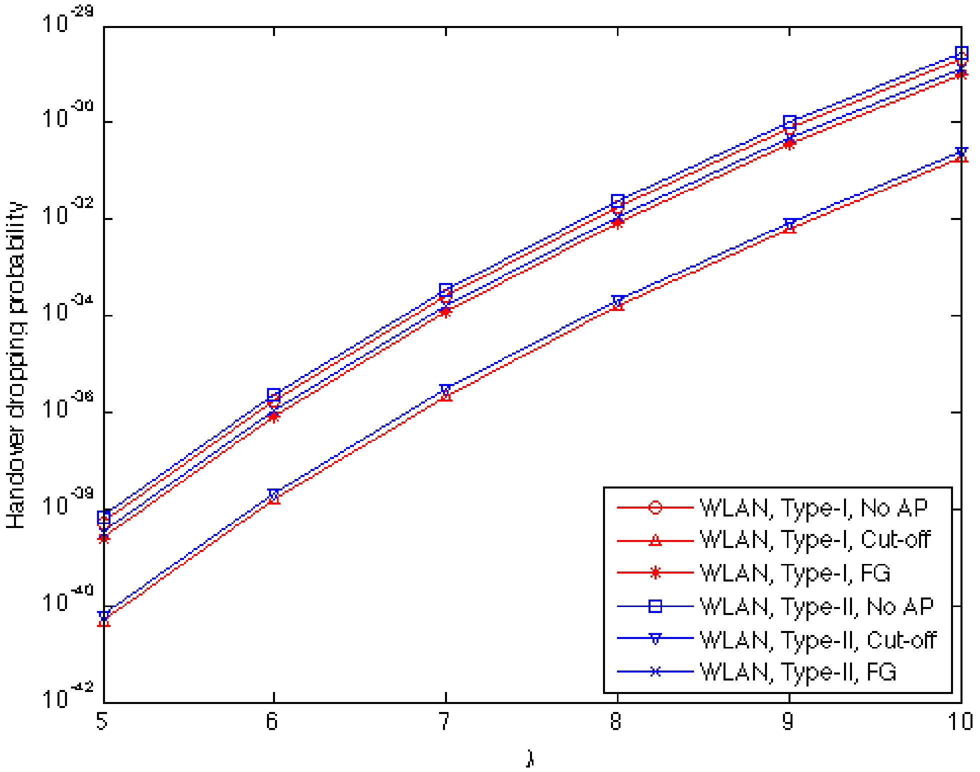


Figure 7.21 Handover dropping probabilities for WLANs with different call admission policy

It can be observed that without any admission policy, i.e. no admission control, the system has the best call blocking performance but worst handover dropping performance. When the cut off admission control policy is applied, the handover dropping performance is the best but it is as a result of sacrifice of the call blocking performance. Fractional guarded channel policy has a mediocre performance on both call blocking and handover dropping performance.

7.4 Summary

In this chapter I built some scenarios to test the models I discussed in chapter 4 and chapter 5 and gave the numerical results. I first set up a cellular/WLAN integrated system with symmetric traffic in section 7.1 by constructing a system with symmetric network topology graph with 3 neighbouring cellular cells, each having an overlay WLAN cell. The numerical results are used to show the viability of the model. Then I further set up a scenario with the same number of cellular and WLAN cells but with different network topology, thus creating an asymmetric traffic flow within the system and the numerical results are given. In section 7.3, I changed the single rate traffic into a multi rate traffic type and with even more WLAN cells this time.

Chapter 8 CONCLUSIONS AND FURTHER WORK

Heterogeneous wireless networks with a hierarchical multi-tier structure as a possible solution for the next generation wireless systems have attracted a lot of research attention in recent years. Mainstream research method for the study of such systems is still to construct a simulation model. In this thesis, I discussed an analytical model as an alternative approach to compliment the simulation models. In the process of model construction, the logical AP/BS level network topology I proposed in Chapter 4 is used to facilitate the derivation of handover traffics.

In this Chapter, I summarize the major research contributions and discuss possible further research work.

8.1 Major Research Results

This research developed a queueing network model for the traffic flow analysis in a heterogeneous wireless network with an emphasis on modelling complex handover traffic flows in the system. An essential modelling technique for the simplification of handover traffic analysis is a new network topology scheme, which effectively converts abstract traffic flows into a clear graphical representation and then into a solvable system of equations. Specifically, the main contributions of this research are summarized as follows:

- System modelling for a cellular/WLAN integrated network: A system model is developed for the integrated network to capture the essential characteristics and enable tractable analysis.

- Network topology scheme: A new network topology scheme is proposed for the analysis of handover traffic flows. Unlike the existing modelling schemes, our modelling scheme benefits greatly from the fixed network topology.

- Analytical QoS evaluation approaches: To properly determine the admission and assignment parameters, the QoS metrics such as call blocking/dropping probabilities are evaluated analytically based on Markov processes.

The significance of this research is it provides a sound alternative approach to the analysis of heterogeneous wireless networks with a hierarchical structure to complement the current research mostly based upon some kind of simulation models. The new network topology scheme used to facilitate the study of complex vertical handover traffic flows in the model is especially useful and is proved to be a very powerful tool in its own merits. This analytical approach will allow the evaluation of arbitrarily small blocking probability which simulation would take too long to quantify.

8.2 Further Work

In this research, I have proposed a new queueing network modelling with the help of network topology scheme to analyse a heterogeneous wireless system consisting of cellular network and WLAN and use it in a number of scenarios to validate the usability of the model.

Although the complementary strength of the cellular network and WLANs had promoted their interworking, the network heterogeneity also poses many research challenges to resource allocation. Research could investigate the following in future:

- In the current model, handover is only triggered by the user mobility. In the next step, the handover triggered by the load-balancing requirement can also be considered.
- Extension to the analysis of switch-flow traffic.
- More study can be considered on heavy tailed distributions for mobile’s residence time.
- Generalization to non-exponential connection holding times.

APPENDIX A. VALIDATION OF THE SIMULATION OF VOICE TRAFFIC WITH ERLANG-B MODEL

The Erlang-B model can be used to model any circuit switched traffic such as telephone traffic in a trunk network where the number of potential users of a link is large. It is a good model for any lost call cleared system. The voice traffic in my research is also modelled as a M/M/n/n queue and can be solved by this Erlang formula.

So the customer in my model is the voice call. λ is the call arrival rate (calls per time unit). $\frac{1}{\mu}$ is the average call holding time. n servers are the link capacity or channels.

At the call level, the user's activity is modelled in my voice model as an ON-OFF process to simulate the activity factor. It consists of 2 states, active (ON) and silent (OFF) stage, with different transition rate from ON to OFF and from OFF to ON stage. To be more specific, an activity factor is the ratio of the ON period over the total time. The value used here, 0.65 [SM05], therefore means that for 65% of the time, the signal will be present at the channel. In Figure 3.3, the voice calls with arrival rate of 0.05 call per second and the mean holding time is 180s.

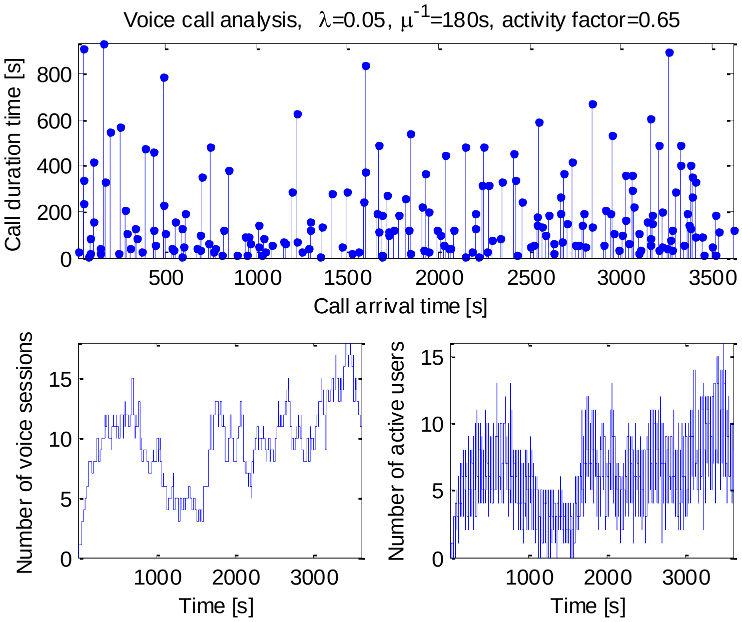


Figure 1 Voice traffic simulation

So according to the discussion above, if the system capacity (the number of channels or servers) is unlimited no calls are rejected due to lack of capacity, the traffic carried in this situation is equal to the offered traffic. In reality, the carried traffic can never exceed the number of the channels (lines). Let's assume the system capacity is 64 channels. It can be observed that in my simulation, whenever a new call arrives while the system is full, it will be lost. So the traffic curve in Figure 3.4 never surpasses the capacity limit line.

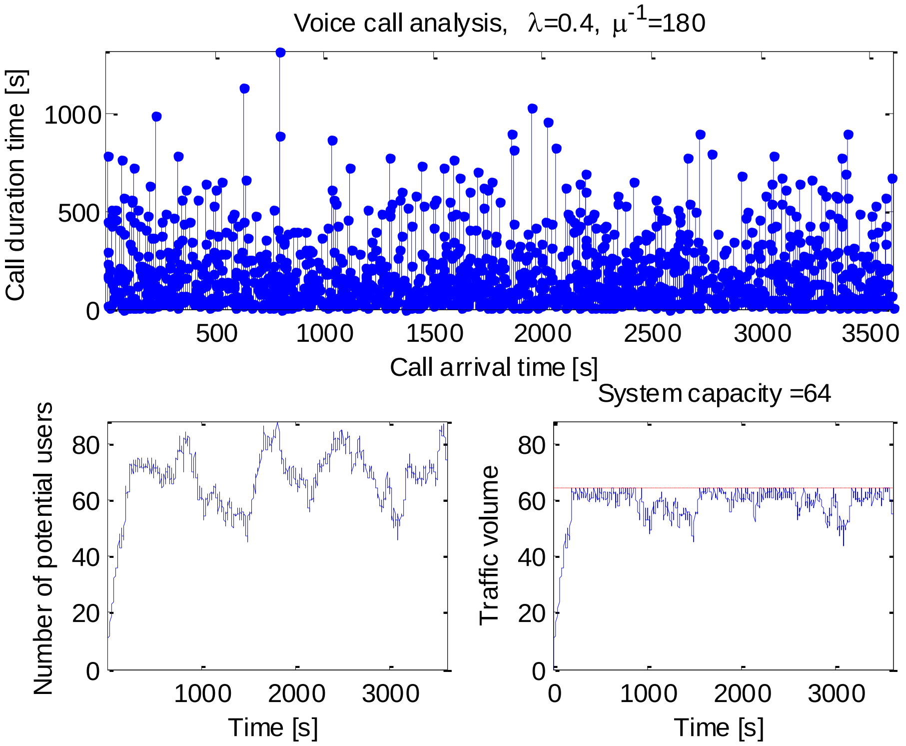


Figure 2 Voice traffic with limited system capacity

Then I run my simulation many times with different traffic intensities (traffic load) ρ by adjusting the value of call arrival rate λ from 0.1 to 0.4, collect the number of the blocked calls and calculate the blocking probabilities for each new traffic load. The theoretical value of the blocking probability is obtained using the Erlang-B formula given in 3.3.1. We can see from Figure 3 that the simulation results match with the theoretical values very well.

Next, I also obtained both time blocking and call blocking values from the simulation and compare them with the values calculated from Erlang-B formula. They all agree with each other as shown in Figure 4, thus verifying the correctness of my voice traffic simulation model.

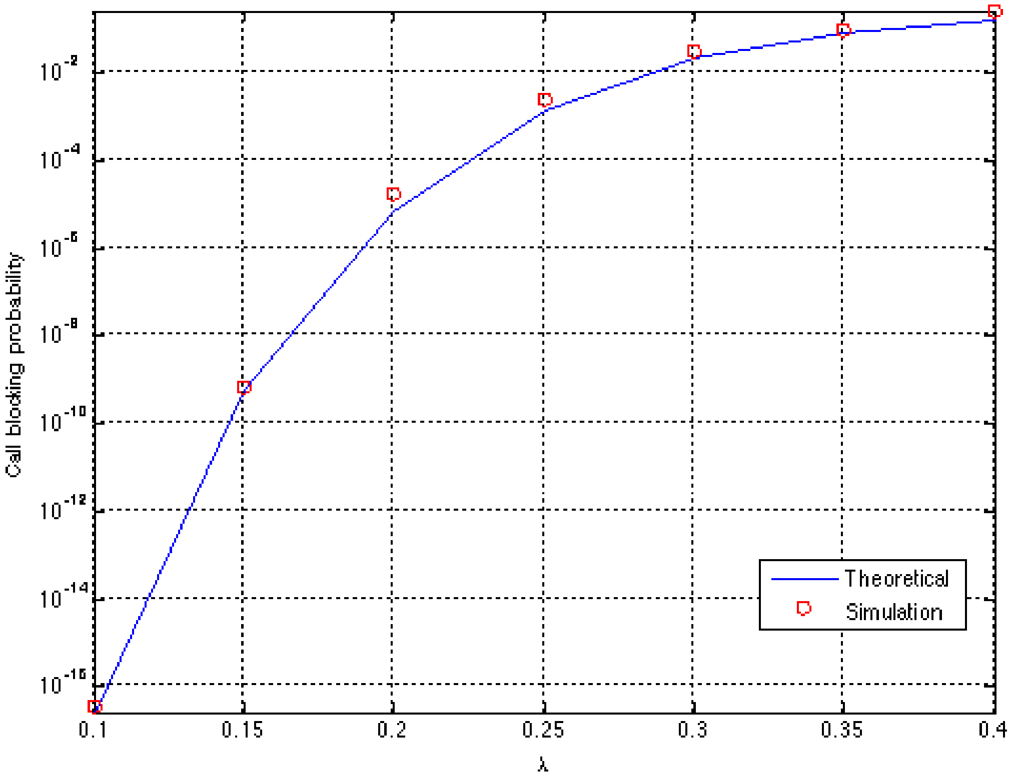


Figure 3 Call blocking rate for M/M/n/n queue

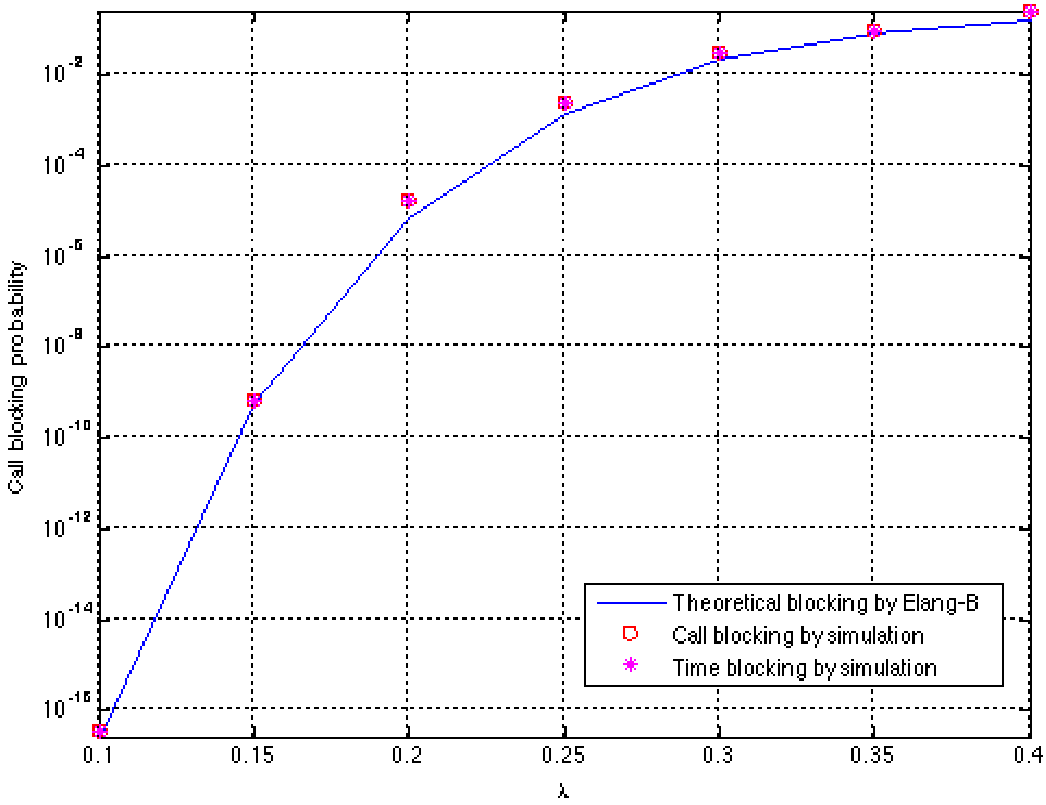


Figure 4 Simulated time blocking, call blocking probabilities together with Erlang-B values

Finally for each call arrival rate λ value, the simulation has been run 10 times and the error rate diagram is plotted against the theoretical results with the smallest observation, lower quartile, median, upper quartile, and largest observation values all in one graph as shown in Figure 5. The box has lines at the lower quartile, median, and upper quartile values. Whiskers extend from each end of the box to the adjacent values in the data—by default, the most extreme values within 1.5 times the interquartile range from the ends of the box. Outliers are data with values beyond the ends of the whiskers. Outliers are displayed with a red + sign.

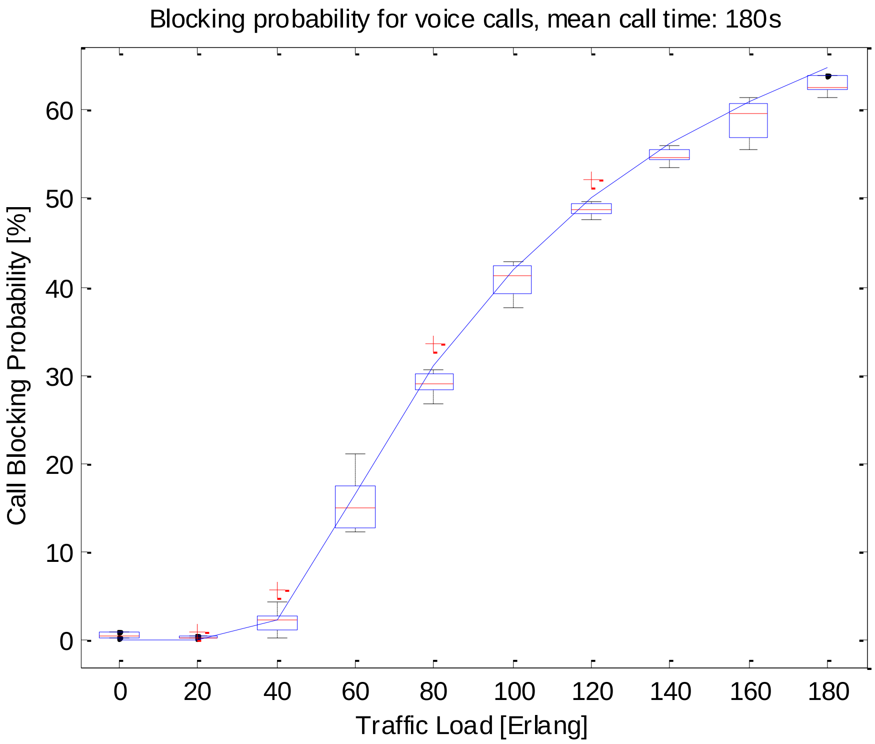


Figure 5 Box plot of the Erlang blocking probability

We can see from figure 5 that the blocking probability values are very stable in my simulation, and follow the Erlang-B theoretical curve very well. So my voice traffic simulation is acceptable.

APPENDIX B. VALIDATION OF THE SIMULATION OF TWO TRAFFIC TYPES WITH MULTI-CLASS ERLANG MODEL

In this part a multi-class Erlang model is used to validate my multi-type traffic simulation. In this simulation, only two types of traffic are presented here as red and blue randomly generated voice calls following poisson distribution as shown in Figure 1. Both arrival rates of the two traffics are set to be 0.1. The mean call holding time for traffic 1 is 180 seconds and the mean call holding time for traffic 2 is 80 seconds. The system capacity is 60 channels. For traffic 1, each call will occupy 2 channels and for traffic 2, each call will occupy 6 channels. Simulation time is 3600 seconds to make sure that the system reaches a steady state.

Two smaller diagrams below the traffic plot are the potential traffic in the system if there is no channel number restrict and the real traffic volume with the certain system capacity. Here the system capacity is 64 channels.

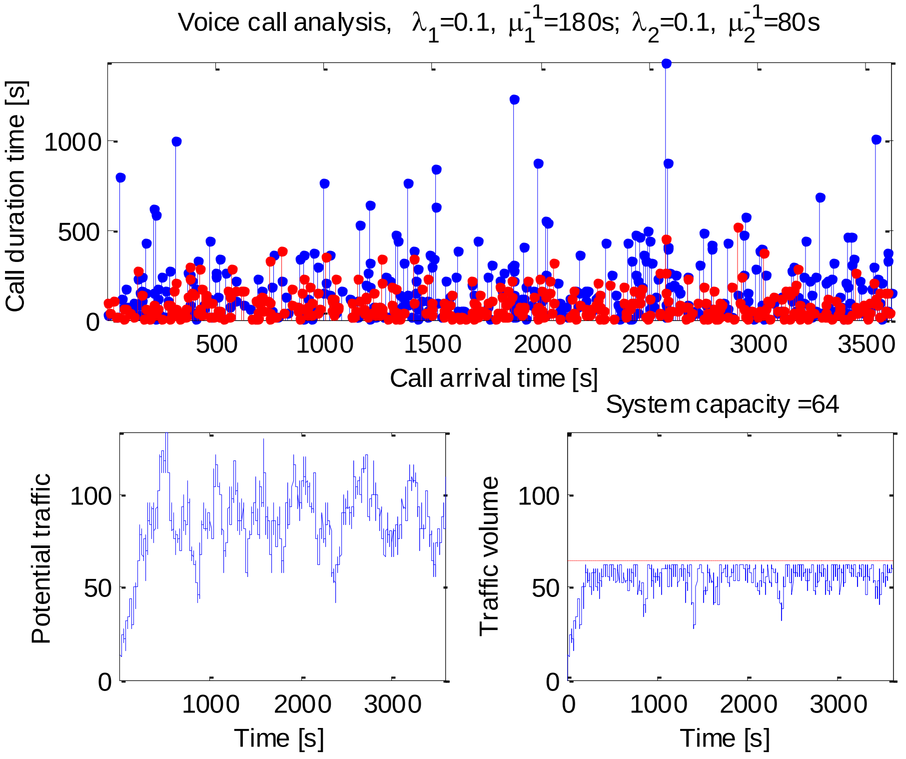


Figure 1 Two traffic class Erlang loss system

I then compare the simulation results with the numerical values calculated based on the Kauffman-Roberts' recursion algorithm in 3.3.1. As we can see from Figure 2, the simulations results are in good agreement with the numerical results from the analytical model.

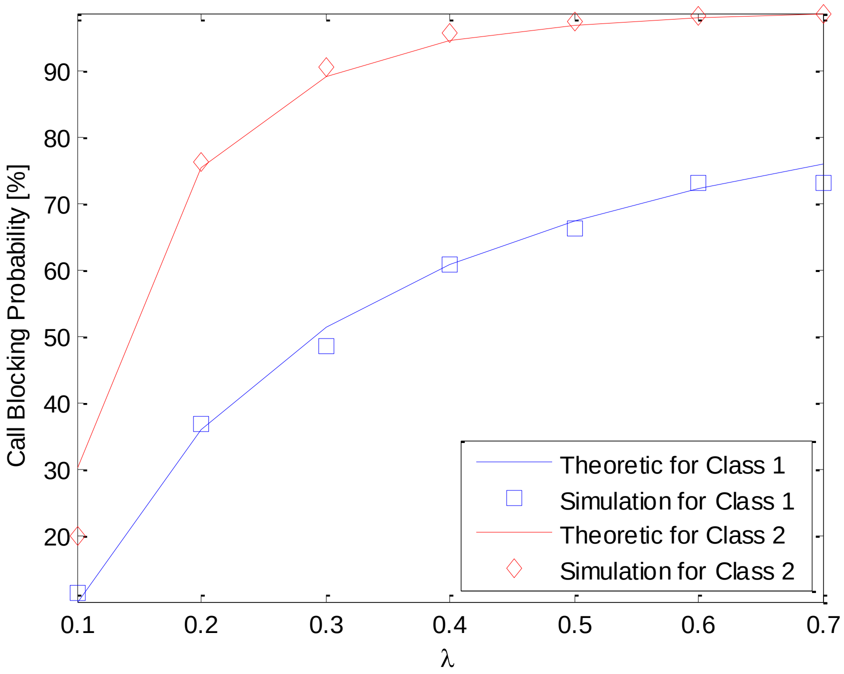


Figure 2 Simulation results compared with numerical calculation

Then the simulation is repeated 10 times, and the final box plot is obtained and shown here in Figure 3 and 4 with the smallest observation, lower quartile, median, upper quartile, and largest observation values all in one graph. The box has lines at the lower quartile, median, and upper quartile values. Whiskers extend from each end of the box to the adjacent values in the data—by default, the most extreme values within 1.5 times the interquartile range from the ends of the box. Outliers are data with values beyond the ends of the whiskers. Outliers are displayed with a red + sign.

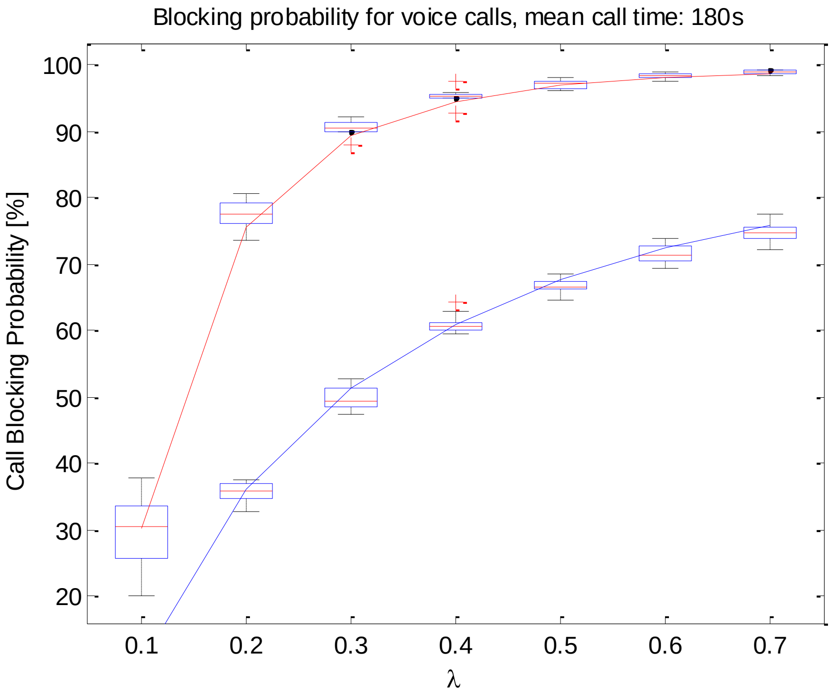


Figure 3 Box plot of call blocking probabilities with λ from 0.1 to 0.7

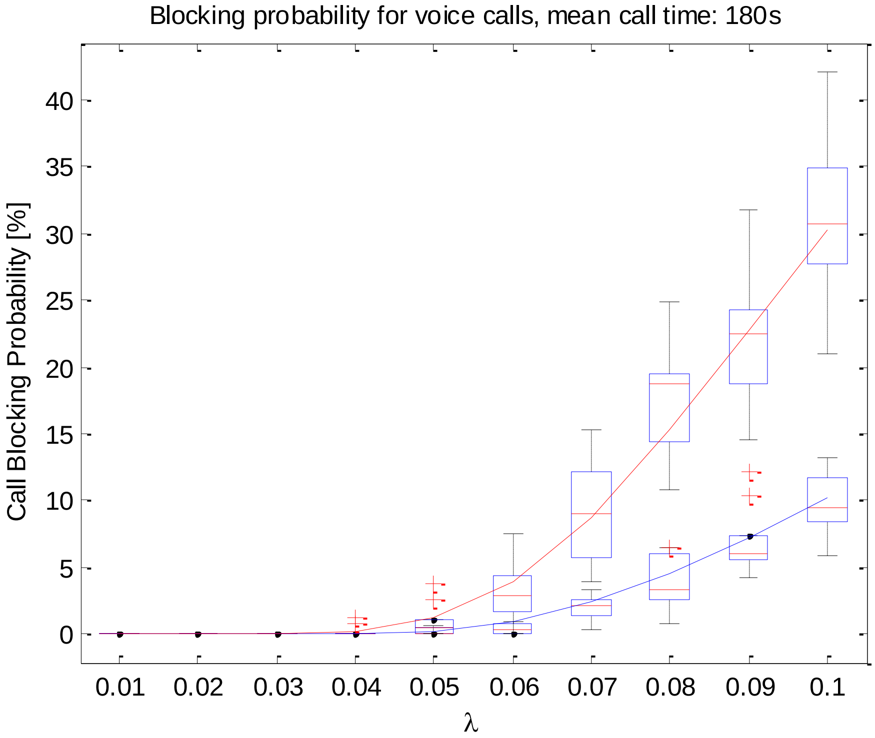


Figure 4 Box plot of call blocking probabilities with λ from 0.01 to 0.1

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