DOCTORAL THESIS

QoS-aware Joint Power and Subchannel Allocation Algorithms for Wireless Network Virtualization

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Abstract

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Wireless network virtualization (WNV) is a promising technology which aims to overcome the network redundancy problems of the current Internet. WNV involves abstraction and sharing of resources among different parties. It has been considered as a long term solution for the future Internet due to its flexibility and feasibility. WNV separates the traditional Internet service provider's role into the infrastructure provider (InP) and service provider (SP). The InP owns all physical resources while SPs borrow such resources to create their own virtual networks in order to provide services to end users. Because the radio resources is finite, it is sensible to introduce WNV to improve resources efficiency. This thesis proposes three resource allocation algorithms on an orthogonal frequency division multiple access (OFDMA)-based WNV transmission system aiming to improve resources utility. The subject of the first algorithm is to maximize the InP and virtual network operators' (VNOs') total throughput by means of subchannel allocation. The second one is a power allocation algorithm which aims to improve VNO's energy efficiency. In addition, this algorithm also balances the competition across VNOs. Finally, a joint power and subchannel allocation algorithm is proposed. This algorithm tries to find out the overall transmission rate. Moreover, all the above alogorithms consider the InP's quality of service (QoS) requirement in terms of data rate. The evaluation results indicates that the joint resource allocation algorithm has a better performance than others. Furthermore, the results also can be a guideline for WNV performance guarantees.

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Contents

List of Figures

List of Tables

Abbreviations

4G	**4**th **G**eneration communication system
BER	**B**it **E**rror **R**ate
BIP	**B**inary **I**nteger **P**rogramming
BR	**B**est **R**esponse
BS	**B**ase **S**tation
CN	**C**ognitive **N**etwork
CRN	**C**ognitive **R**adio **N**etwork
EE	**E**nergy **E**fficiency
FDM	**F**requency **Division** **M**ultiplexing
IaaS	**I**nternet **as a** **S**ervice
InP	**I**nfrastructure **P**rovider
IT	**I**nformation **T**echnology
ISI	**I**nter **S**ymbol **I**terference
ISP	**I**nternet **S**ervice **P**rovider
MAC	**M**edia **A**ccess **C**ontrol
MNO	**M**obile **N**etwork **O**perator
MNV	**M**obile **N**etwork **V**irtualization
MVNO	**M**obile **V**irtual **N**etwork **O**perator
MVNP	**M**obile **V**irtual **N**etwork **P**rovider
NE	**N**ash **E**quiblium
NVE	**N**etwork **V**irtualization **E**nvironment
NVS	**N**etwork **V**irtualization **S**ubstrate
OFDMA	**O**rthogonal **F**requency **D**ivision **M**ultiple **A**ccess
OTT	**O**ver **T**he **T**op

PRB	**P**hysical **R**esource **B**lock
QoS	**Q**uality of **S**ervice
RAN	**R**adio **A**ccess **N**etworks
SDM	**S**pace **D**ivision **M**ultiplexing
SDMA	**S**pace **D**ivision **M**ultiple **A**ccess
SDN	**S**oftware **D**efine **N**etwork
SNR	**S**ignal to **N**oise **R**atio
SP	**S**ervice **P**rovider
TaaS	**T**elecommunication **a**s **a** **S**ervice
TDM	**T**ime **D**ivision **M**ultiplexing
TDMA	**T**ime **D**ivision **M**ultiple **A**ccess
UE	**E**nd **U**ser
VN	**V**irtual **N**etwork
VNP	**V**irtual **N**etwork **P**rovider
VNO	**V**irtual **N**etwork **O**perator
VO	**V**irtual Network **O**perator
VPN	**V**irtual **P**ersonal **N**etwork
WNV	**W**ireless **N**etwork **V**irtualization
XaaS	Everything **a**s **a** **S**ervice

Chapter 1

Introduction

The virtual concept was first introduced by Christopher Strachey in the early 1960s [1]. Generally speaking, virtualization is the process of creating virtual versions of physical resources that emulate the same physical characteristics. Nowadays, network virtualization attracts a growing number of industries and academics. Following the Information Technology (IT) context, virtualization such as virtual memory, storage and virtual machines, network virtualization is considered as a long term solution to figure out the gradual ossification problems that exist in the current wireless networks. In addition, it also attracts major attention in how to model the next generation network pattern, that can replace the current Internet [2].

Network virtualization is a process that aggregates virtual resources in order to create virtual networks (VNs). Such virtual networks are able to coexist on the same infrastructure. Moreover, every VN is isolated to the others. The individual VN is similar to a general network and it is not necessarily aware of the underlying virtualization progress. A single VN can deploy its own specific protocols and architectures which could not be the same as other coexisting VNs. In addition, network virtualization also allows complete end-to-end administration control for operators over their VNs.

Current wireless networks have made tremendous achievements after decades of developments. However, increasing numbers of services bring more and more challenges to the existing networks. In addition, due to the characteristics of radio frequency and antenna size, the most commonly used frequency bands of current wireless networks are from 300 MHz to 5 GHz. Therefore, the spectrum resource is finite for wireless communication. Hence, it makes more sense improving the resource utilization. Wireless network virtualization is introduced to overcome this problem as a long term solution.

1.1 Background

In recent years, a growing interest in wireless network virtualization has resulted in numerous applications, test-beds and projects. They are not only providing a new network architecture, but also aiming to solve the long term problem of current wireless networks. Because of an increasing number of services that came into the market, a shortage of spectrum and power resources occurs obviously. Thus, to use the resources efficiently is one of the most important issues in wireless network studies. As mentioned before, wireless network virtualization is considered as a long term solution to improve current wireless network performance as well as to provides a feasible method to overcome the resources shortage problem of current wireless networks.

There are several challenges for WNV, for example isolation, embedding, resource allocation, signalling and mobility management [3]. The isolation can be relatively easier to achieve on hardware basis. However, in wireless networks any changes in one network may cause high interference to other neighbouring networks [4]. Moreover, wireless networks overlapping might cause cross-layer and co-layer interferences [5]. Authors in ref. [6] deploy space and time separation approaches on a test-bed in order to study the isolation problem in WNV. Compared to the isolation issue, more investigations have been done regarding the virtual network embedding [7–11]. The authors in ref. [12] take online requests into account when proposing the embedding algorithm. Furthermore, improving resources utility is also crucial and attracted an increasing attention from both academic researchers and industry. In other words, the resource allocation problem is one of the most significant issues of WNV. This thesis mainly focuses on the resource allocation problem and proposes three resource allocation algorithms for WNV. The detailed challenges will be introduced in Chapter 2.1.5.

A wireless virtual network environment consists of infrastructure providers (InPs) who own all physical entities (e.g. base station, transmission tower and spectrum license, etc.) and virtual network operators (VNOs) who do not have any physical resources. The InP has interests to share its spare resources with multiple VNOs. By means of leasing resources from the InP, VNOs are able to create their own virtual networks in order to provide services to their end users. In particular, one InP is allowed to share resources to more than one VNO while a VNO can borrow resources from more than one InP. It is clear that both InPs and VNOs benefit from a WNV. From the InP's view, it can concentrate on the maintenance of the physical equipment and save manpower. Moreover, the overall resource utilities can be improved. On the other hand, VNOs save a great amount of investment in the hardware and fundamental construction by taking advantage of resource sharing. In addition, VNOs have the fully control of their VNs. Namely different VNs are allow to define their own topologies, protocols, flow scheduling as well as the quality of service (QoS) requirement depending on the network operators.

WNV separates the management and business roles of the Internet service provider (ISP) by identifying the following roles: the virtual network provider (VNP) borrows virtual resources from one or more InPs, it manages and operates VNs according to the needs of the virtual network operator. In addition, the VNO concentrates on business by using the VNs to other end users services. In a business model, an SP can be formed by VNPs and VNOs.

A VN is the fundamental component of a network virtualization environment. It is an aggregation of virtual nodes connected by a set of virtual links to compose a virtual topology. FIGURE 1.1 shows the basic structure of a WNV. The VNP rents InP_1's and

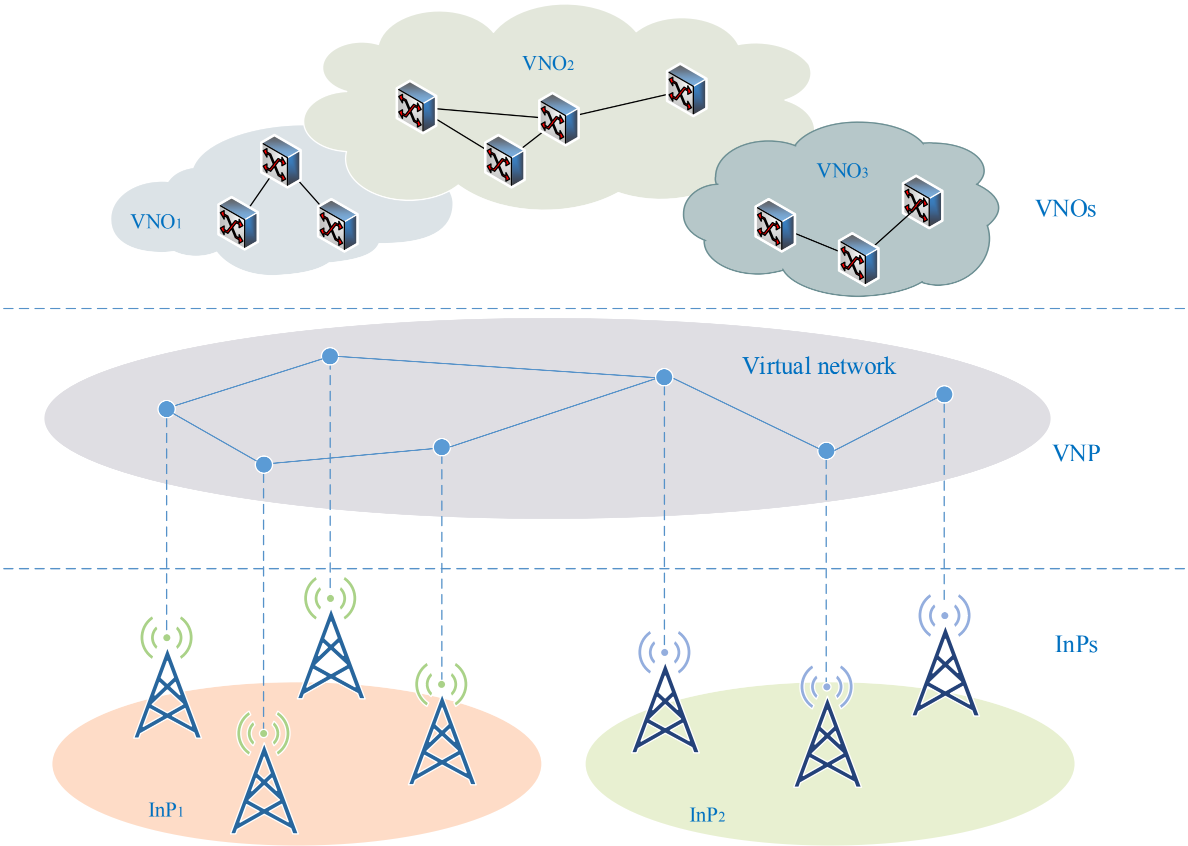

FIGURE 1.1: Wireless Network Virtualization Architecture

InP_2's physical resources in order to create its own VN. Then one or more VNOs can form their own VNs and provide access services to end users.

There are several principles that can be proposed to the future networks by network virtualization. According to ref. [13], the coexistence of multiple VNs from different SPs is one characteristic of network virtualization environment (NVE). In addition, one or more VNs can be created by another VNP. This is known as recursion or nesting of VNs [13]. Moreover, a child VN is able to inherit the architectural attributes from a parent VN.

The current cellular mobile network's standard is the Long Term Evolution Advanced (LTE-A). It is also known as the forth generation telecommunication technology (4G). The 4G standard employs orthogonal frequency division multiple access (OFDMA) as its modulation scheme. OFDMA is a multi-user modulation scheme which encodes digital signals onto multiple low frequencies channels. A large number of orthogonal subcarriers are used to carry signal on several coexisting channels, which are known as subchannels in the media access control (MAC) layer. The fundamental advantages of OFDMA are inter symbol interference (ISI) elimination, signal-to-noise ratio (SNR) improvement and severe channel conditions management simplification, etc. This thesis proposes three resource allocation algorithms that are based on an OFDMA WNV transmission system.

Considering all the benefits of WNV, the research in this thesis aims at finding out how to effectively allocate resources. In addition, this thesis focuses on designing QoS-aware resource allocation algorithms. It also proves that different resource types have different effects to the overall system performance. By setting different objects to each algorithm, it provides more opportunities to deploy the most suitable algorithm to a specific virtual network.

1.2 Motivation

Wireless network technologies increased in use enormously, in result of that radio resources have decrease dramatically. As mentioned before, the spectrum of a majority of applications that used in wireless networks are between 300 MHz to 5 GHz. The amount of radio spectrum assigned to cellular networks is much smaller. Thus, to efficient use such radio resources is a necessity. WNV is one of the methods that can increase the resources utilization. In addition, it is able to overcome the resistance of the current Internet to fundamental changes [14].

Future Internet architectures will be based on the infrastructure as a service that decouples the importance of current ISPs' into two roles: the InP who deploys and maintains the network equipment and the SP that is responsible for providing end-to-end services to users [15]. In addition, WNV separates the management and business roles of the ISP by identifying two main entities: the VNP, which leases resources from one or more InPs and the VNO who manages and operates VNs according to the requirements from its end users.

Both commercial market and research areas have plenty interest of studying wireless network virtualization. In wireless networks, an infrastructure based test-bed is a powerful tool for recognizing and evaluating new technologies as well as proposing new architectures. By means of wireless network virtualization test-bed, the theoretical research and practice implementation are strongly connected. This is because the proposed new technologies or architectures can be deployed on a virtual network easier regardless of complicated physical infrastructure layouts. In addition, the isolation between VNs provides an opportunity to operate multiple experiments simultaneously. This characteristic allows the deployment and running of experiments in a real infrastructure without disturbing the usual network services [16].

From the commercial market's view, capital expenditure (CapEx) and operating expense (OpEx) can be lowered significantly due to the resource sharing enabled in WNV. It is found that up to 40% of CapEx and OpEx can be saved over five years if telecom operators deploy WNV [17] while the authors in [18] estimate that 20% to 30% of CapEx can be reduced by antennas and sites sharing. Moreover, if the whole radio network is shared, the CapEx can be decreased by an additional 10%. In general, the OpEx can be reduced significantly but varies depending on different policies. In short, there will be a great saving of CapEx and OpEx by deploying WNV.

1.3 Contribution

The research studies the resource in terms of power and subchannel allocation algorithm for wireless network virtualization with QoS consideration. To the best of the author's knowledge, it is the first attempt to apply QoS constraint to OFDMA-based WNV. This thesis proposes three dynamic resource allocation algorithms with QoS constraint. Based on the modelling of the WNV system, the first algorithm is designed for subchannel allocation. Followed by, a power allocation algorithm is proposed. Finally, a joint power and subchannel allocation algorithm is introduced. The main contribution of this thesis are described below.

- Subchannel allocation algorithm

  In this algorithm, the amount of power that is assigned to each VNO is assumed to be equal. Under this condition, one InP is willing to share its own spare resource with several VNOs. This subchannel allocation algorithm aims to maximize the total throughput of the InP and VNOs. To be noticed that the InP is willing to lease resources only when its own users' requirement are satisfied. In this algorithm, the InP owns a fix amount of subchannel and the optimization problem is formulated to a binary problem. Because each subchannel can achieve different data rates by different transmission paths, the algorithm is trying to find out the best assignment of each channel to each VNO in order to maximize the total throughput.

- Power allocation algorithm

  This algorithm aims at allocating power effctively. Similar to the subchannel allocation algorithm, one element is assumed to be fixed. In this case, the amount of allocated subchannels of each VNO is considered to be the same. However, this algorithm aims maximizing the energy efficiency of each VNO. In addition, the InP's QoS requirement needs to be satisfied. The energy efficiency is defined as how many payload bits can be successfully delivered per joule energy. This problem is solved by gaming theory. The reason to adopt this method is that the individual VNO's performance is being considered. Under this consideration, VNOs would not know each others allocation schemes. This is called non-cooperative game. Namely each VNO tries to maximize its own utilities. This algorithm aims to find out a balance between VNOs rather than maximizing the overall throughput. One of the evaluation results shows that this approach balances VNOs rather than achieving the maximum total data rate.

- Joint power and subchannel allocation algorithm

  By proposing and analysing the individual resource element allocation algorithm, a joint resource allocation algorithm is proposed. According to the Shannon Formulation, the final achievable data rate is determined by more than one factor (e.g. bit error rate, power and bandwidth). Thus, it is more sensible to provide a joint power and subchannel allocation algorithm. This algorithm first assumed the fixed power allocation scheme in order to calculated the optimized subchannel allocation scheme. Then by applying this optimized subchannel amount to calculate the power allocation until the overall throughput reach the optimum point. In compared the three resource allocation algorithms, the joint power and subchannel allocation algorithm achieves the best performance.

Although the three resource allocation algorithms are modelled by different methods, the aim is to find out the best results across the three solutions. For example, the power allocation algorithm is solved by gaming theory and the subchannel allocation algorithm is formulated into a binary integer programming. However, the results indicate that by using binary integer programming the overall throughput can be maximized even if it might not consider the individual VNO's performance. On the other hand, thought the total data rate can not by applying gaming theory, it achieved the highest balance across VNOs.

1.4 Structure of the Thesis

The rest of the thesis is organized as follows.

Chapter 2 provides a brief overview of the wireless network virtualization. Section 2.1 introduces the research background and the related work regarding to the research topic is illustrated in Subsection 2.3.3. It also discusses different types of resource allocation algorithms in different network architectures. Chapter 3 introduces a subchannel allocation algorithm for WNV which aims to maximize the total throughput of the transmission system. Chapter 4 provides a power allocation algorithm and the objective is to achieve the highest energy efficiency. Chapter 5 extends the work of Chapter 3 and Chapter 4, it proposes a joint power and subchannel allocation algorithm for WNV with the QoS consideration. The results show in Chapter 5 illustrates that the joint algorithm is able to achieve the best performance.

Chapter 2

WNV Background Knowledge and Literature Review

As mentioned before, the virtual network environment consists of InPs that own all physical entities (e.g. infrastructures, base stations and spectrum licensing) and VNOs who do not own any physical resources. An InP is willing to share its spare resources with VNOs. The VNO then creates its own VNs in order to provide services to their users with leased resources from the InP. It is to be pointed out that one InP can rent resources to more than one VNO while one VNO can borrow resources from more than one InP. Both InPs and VNOs benefit from WNV. For example, the InP can concentrate on the maintenance of the physical equipment as well as save manpower. In addition, this resource sharing acheme also improves the resource utilities and generates profits. On the other hand, VNOs save a great number of investment on the hardware and fundamental construction with resources sharing [19]. Moreover, VNOs have the fully control of their own VNs. Different VNs can define their own flow scheduling, QoS as well as topology depending on the VNOs' requirements [13].

2.1 Overview of WNV

In this section, projects related to WNV are introduced in detailed. In addition, software defined networking (SDN) and OpenFlow are presented. Furthermore, the business model of a WNV is introduced. After an illustration of the challenges, the design goals of WNV research is provided.

2.1.1 Projects

The research activities of future Internet architecture pay more and more attention on WNV. For example, 4WARD [20] from Europe, VINI [21] and GENI [22] from the United States, AKARI [23] and AsiaFI [24] from Asia are all interested in network virtualization. Some of the projects are introduced in detail afterwards. VINI is a VN infrastructure based on PlanetLab. It allows researchers and developers deploy, run and test their own protocols and services on a large scale network. GENI is also a novel architecture that supports a wide range of experimental protocols. The AKARI architecture design project aims to implement the basic technology of a new generation network while network virtualization has been seen as one of its principle applications. The AsiaFI was founded to coordinate research and development on the future Internet where network virtualization is its major research topic [3].

There are a number of project works on the different areas of network virtualization such as virtualization on different network layers or network virtualization technologies. VNET [25] focuses on the link layer virtualization. This project has developed a simple layer two virtual network for virtual machine grid computing. AGAVE [26] has studied a network layer virtualization which covers data control and plane functions. On the other hand, FEDERICA [27] works on the VN architecture in a management approach. In addition, GENI [22], PlanetLab [28] and CABO [29] are looking on the granularity of network virtualization. The above three projects are relatively important to WNV research, thus further details are introduced below.

- GENI:

  Global Environment for Network Innovations (GENI) is a virtual laboratory for networking research and education [22]. It is ideal for exploring network scale, as a result promoting the network security, services and applications innovations. According to ref. [22], this project allows researchers instalingl their own protocol software on compute resources. As a result, they can run their own protocols over the current network protocol.

  The project introduces wireless network virtualization on the GENI test-bed. Space division multiple access (SDMA), time division multiple access (TDMA) and frequency division multiple access (FDMA) are used for WNV technologies and VN slicing. It is a good opportunity for reserchers to customize their VNs regardless of the current network's protocol and on-going traffic.

  GENI is a shared test-bed because of slicing. It means the possibility of running different projects simutaneously. A GENI slice is an isolated unit for experiments. Only the members of a GENI slice can modify the experiments in the specific slice. GENI experimenters aggregate compute resources into a container of the slice, then they use these resources to run their experiments. In addition, the access slice authority belongs to the creator of the slice. The creator has the right to determine members of the slices. Usually, the project leader automatically becomes the slice member. GENI provides the practicality of VN isolation. In another words, a VN is fully isolated to another. This feature is essential for the author's algorithm because the algorithms are all based on fully VN isolation.

- PlanetLab: One of the main objectives of PlanetLab is to provide an overlay network test-bed. A remarkable feature of PlanetLab is the slice ability. It is a crucial ability and design principle in WNV, which is important to both wired and wireless network virtualization. Research groups can request a PlanetLab slice to experience their own services, such as documents sharing, network embedding, content distributed networks, routing and multicast overlays, QoS overlays, scalable object location, scalable event propagation, anomaly detection mechanisms and network measurement tools [28].

The PlanetLab benefits researchers in which they can examine new services and technologies based on a real wireless network condition. The example services listed above are all benefited from the widely distributed Internet: such as the example applications can inspect and respond to the network behaviours by approaching to data sources or data sinks, or from distributing at different administrative boundaries.

The PlanetLab machines are based on Linux operating system. They run a common software package which includes mechanisms for bootstrapping nodes and distributing software updates; a collection of management tools that monitor node health, audit system activity, and control system parameters; and a facility for managing user accounts and distributing keys [28]. This distributed software package is called MyPLC where researchers can build their own personal PlanetLabs.

To support distributed wireless network virtualization is another key purpose of this software package. In other words, the software package allows allocating a PlanetLab's slice to any applications. This features enables an application can run over any of the globe distributed machines. In addition, multiple applications are able to operate on different PlanetLab's slices. In short, PlanetLab test-bed provides opportunities to resercher to study WNV on a realistic wireless network enviroment.

- CABO: This project improves and prompts InPs and SPs separation. It is the first project which allows full mapping of virtual routers. In other words, virtual routers are able to move from one physical node to another. Moreover, CABO also supports complete virtualization in which SPs are able to provide end to end services over multiple infrastructure. Finally, it allows customization of SPs when they provide services to their own users. In addition, this project guarantees the services that are provided by virtual SPs.

The above three projects garantee the assumtion of the resource allocation algorithms that are proposed in this thesis: fully isolation, slicing and virtual SP services gurantees. Furthermore, because the resource allocation algorithms is desined based on mathmetic analysis, it is more sensible to deploy the algorithms on the test-bed that mentioned above.

2.1.2 Software Define Networking and OpenFlow

Software Define Networking (SDN) is considered as a promising technology for virtual networks, which allows networks to be programmable by external applications [30]. This emerging network architecture focuses on the following features [31]:

- Networks are programmable by applications.
- A network controller is separated from specific physical elements.
- The network controller is centralized and can have a view of the overall network.
- Open interfaces between the controller and data devices.

In SDN, the network controller is logically separated from the physical routers and switches, etc. Hence, network operators can program a high level controller, which is able to define the behaviour of the whole network. In contrast, transitional networks must codify functionalities according to physical level devices configurations. The advantage of SDN is that the network administrator is able to control the network traffic via a programmable central controller without accessing physical devices. In addition, an SDN configuration also can physically remove the network controller from the data forwarding hardware. In another words, the switch forwards traffic packets while a separated server run network control plane [3]. This separation allows the controller operating on a better performance platform.

A standard communication interface called OpenFlow [32] is defined between the network controller and the traffic forwarding layers of the SDN architecture. OpenFlow enables directly accessing as well as operating on the forwarding part (e.g. switches and routers). In addition, multiple routers can decide the traffic packets path by running the specific software. Therefore, the network switch and router vendors have attempt to support OpenFlow standard due to this feature.

Ref. [33] introduces the concept of applying SDN to cloud radio access network (C-RAN). C-RAN is a software-defined RAN mechanism which includes a wireless spectrum resource pool (WSRP), a cloud computing resource pool (CCRP) and an SDN controller [3]. In this architecture, several physical remote radio units (pRRUs), that are distributed at different locations are combined into the WSRP. One pRRU is split into multiple virtual RRUs (vRRUs) where they can coexist onto the same pRRU. It is clear that the WSRP and CCRP can create a complete virtual RAN and the SDN controller would have the control responsibility to this RAN. Moreover, authors in ref. [34] consider all physical base stations (BSs) in a geographical area in order to introduces a more general software defined RAN.

2.1.3 WNV on different technologies

- LTE Virtualization

  The basic framework of cellular network virtualization can be found in [35]. It proposes the concept of virtual nodes, virtual links and virtual radio where the virtual nodes and links are managed by a centric management method. Authors in [35] clearly defined the data and control plane separation. Thus different protocols and management strategies can execute on multiple virtual nodes and virtual links. This paper provides the preliminary conception of cellular network virtualization. However, virtual network isolation and virtual resource allocation are not introduced in practice.

Most of the current cellular network virtualizations are based on 3GPP LTE-A transmission systems. Similar to the node virtualization, the enhanced NodeB (eNodeB) in 3GPP LTE-A is virtualized and have many approaches [36–38]. In addition, ref. [38] is a typical example of LTE-A based cellular network air interface virtualization implementation. Ref. [39], [40] and [37] introduce virtualization of LTE. The key idea is to virtualize the enhanced NodeB (eNodeB). An entity called hypervisor is proposed on the top of physical resources in BS. The hypervisor virtualizes an eNodeB into several virtual eNodeBs. The hypervisor is responsible for allocating resources blocks to different virtual eNodeBs. Each virtual operator generates an virtual eNodeB and share the resources based on QoS requirements and return feedback (e.g. channel conditions, traffic loads, priorities, etc.) to the hypervisor. Afterwards, the hypervisor assigns the resources or physical resource block (PRB) to virtual networks according to these feedbacks. In addition, there are two important entities that are equipped on a hypervisor: the spectrum configuration and bandwidth estimation (SCBE) and the spectrum allocation unit (SAU) [3]. The SCBE is logically located on each virtual eNodeB in order to estimate the spectrum requirements of a virtual eNodeB. At any time interval, a SCBE estimates the required spectrum bandwidth based on an exponential moving average of each VNOs and sends the estimation back to the SAU. Then the SCBE configures the spectrum for each virtual eNodeB.

In LTE-A MAC scheduling, a PRB is the smallest unit that can be allocated to users. The hypervisor splits the spectrum across multiple virtual eNodeBs which is equal to the scheduled PRBs among virtual eNodeBs. The PRBs are scheduled based on bandwidth, interference, transmission rate, power, traffic, channel conditions, VNOs' requirements, pre-defined agreement, etc. [13]. The SAU is used to schedule the spectrum across virtual eNodeBs according to the pre-defined agreement. There are four types of pre-defined agreement: 1) fixed scheme where a fixed amount of spectrum is allocated to all virtual eNodeBs; 2) dynamic scheme where the spectrum is allocated according to the virtual eNodeBs' requests and will not be over an upper bound limitation; 3) best effort where a minimum requirement is guaranteed; 4) best effort without guarantees where the spectrum is allocated under a pure best effort scheme. Ref. [38] proposes a practical mechanism approach in LTE-based virtualization. However, factors such as signalling, isolation, embedding and higher layer virtualization still need to be enhanced.

Ref. [41–43] adopt a similar mechanism with ref. [36], but they expand the several specific issues. Authors in [41] investigate the multiplexing gain of LTE-A virtualization. By analysing and simulating the eNodeB virtualization, they propose a general multi party model for real time services which enables the centralized spectrum sharing with spectrum estimation. The authors in [42] implement load balancing techniques on the framework that is proposed by [36]. By means of a dynamic load balancing mechanism, the high loaded eNodeBs can spread the excessive traffic onto multiple low loaded virtual eNodeBs, which results in a remarkable gain of system performance. The paper also analyse applications(e.g. voice over IP, online video, HTTP and FTP) on LTE virtualization.

The concept of decoupling controllers and data plane in LTE virtualization since SDN has been proposed in [33, 34, 44–46]. In addition, the technology (i.e. OpenFlow) of realizing SDN is also introduced to LTE virtualization [47]. However, it should be pointed out that SDN and OpenFlow is not the same as network virtualization. SDN is a mechanism that can be applied for WNV, but its use is not essential realize network virtualization [3].

The authors in [45] and [48] provide an architecture level plans for LTE virtualization. Ref. [45] researches the network packet processing and expands the FlowVisor into CellVisor. It provides more flexible slicing resource categories for base stations and eNodeBs. Ref. [48] mainly focus on eNodeB virtualization. The eNodeB is split into multiple virtual eNodeBs under FlowVisor policy. In addition, the same amount of controllers are allocated to the related SPs or VNOs. According to FlowVisor scheme, the flows will be stopped when an SP sends information to the eNodeB and maps flows to the available eNodeB. Similarly, FlowVisor only forwards the traffic load from the eNodeB to the controller. Therefore, the SP does not realize the eNodeB has been split into several virtual eNodeBs.

A simulation result of LTE virtualization is provided in [37]. The result shows that delay can be reduced with less effects to throughput after applying virtualization on LTE-based networks. In addition, it points out that there are two advantages of LTE virtualization: sharing the same infrastructure will reduce the power consumption and the VNOs can easily change their virtual networks on a real time basis.

- Wireless local area network (WLAN) Virtualization

  In ref. [49], the authors design a WLAN virtualization approach called virtual WiFi solution to support complete WLAN functionalities within a physical machine and also expand virtual network embedding to virtual WiFi. The work uses Kernel-based virtual machine to virtualize the WiFi devices into virtual machines (VMs) which can behave as a virtual WLAN equipment. It can be seen from the simulation results that the solution is able to maintain manifold VNs without performance compromise. Each VM can establish its own wireless connection. However, some VMs have attempts to migrate from the original devices to other devices. Ref. [50] proposed a framework of VMs migration. In this framework, the migrated VMs maintain the connection by deploying them on other physical access points (APs) [51]. In addition, some physical nodes may want to aggregate several virtual APs while virtualization technologies can be used to manage those aggregated APs [50].

Ref. [52] and [53] introduce the architecture of virtual WLANs while the author in [54] proposes an open source virtualization technique to implement WLAN virtualization. In addition, the TDMA-based WLAN approaches are discussed in [55] and [56] while an SDMA-based virtualization solution is provided in [57]. Evaluation of the space separation scheme indicates that the solution provides higher efficiency and less coupling between experiments. Moreover, researches on virtual APs are very popular. Ref. [58] and [59] discuss how to apply efficient mobility management through virtual APs. Ref. [60] proposes an optimal and fair method to partition the limited resources rather than pooling the spectrum.

- WiMAX virtualization

  IEEE 802.16e standard also know as WiMAX has been studied in virtualization. Ref. [61] proposes a virtual network traffic shaper for WiMAX virtualization air time fairness. The fairness problem also has been considered in [62] where the authors propose two algorithms for supporting uplink group fairness in virtual WLANs. The evaluation results indicate that the algorithms can achieve up to 40 % improvemen by WLAN virtualization. A virtual BS architecture is proposed in [63] and the authors in [13] study a virtualization substrate for WiMAX networks.

  A typical example of WiMAX virtualization has been studied in [13]. The authors introduce a network virtualization substrate (NVS) as a virtualization solution not only for WiMAX but also compatible to other cellular networks. There are two schedulers running on MAC layer in NVS: slice and flow schedulers. The slice scheduler enables bandwidth-based slicing and resource-based slicing in order to support isolation. The slice scheduler determines slices which can maximize the VNP's utility. The utility is determined by the agreement between VNPs and

VNOs. By choosing the most suitable slice, the revenue of the InP can be maximized and the individual slice requirement is satisfied without disturbing other slices. Then the flow scheduler chooses the flow from the specific slice so that the slice can customize its own flow schedule policy. NVS proposes three models: scheduler selection, model specification and virtual time tagging. Either scheduler selection or model specification enables flow schedule customization while in virtual time tagging, the slice can have its own flow scheduler. NVS provides a practical WiMAX virtualization mechanism. However, the current WiMAX network virtualization needs more improvement on the MAC layer. Moreover, the NVS does not discuss network layer virtualization and the fully virtualization has not been supported in NVS.

To continue the NVS research, ref. [64] introduces CellSlice system. CellSlice moves the slice scheduler to a gateway in order to improve the MAC layer scheduler in NVS. In addition, there are several advantages of CellSlice due to its dynamically selection of flow parameters. First of all, a slice request can be satisfied at the same time of isolation. Second, a resource allocation fairness can be achieved by dynamically arriving and departing flows. Finally, the resource utility can be maximized.

In ref. [13], the slice scheduling are based on a per OFDM frame while the authors in ref. [65] provide a per subcarrier basis slices scheduling. In addition, the algorithm that is proposed in ref. [65] only slices part of the wireless network resources and rents them to VNOs. The resource allocation assignment is formulated into a general binary integer programming (BIP) problem which aims to find out the best assignment of subcarriers. Each VNO's virtual network is assigned a minimum number of subcarriers when the InP's requirement is satisfied. In contrast, the power allocation scheme is studied in [66]. The problem is more complicated in which the author uses multi-steps dynamic optimization solution to solve. In another words, the subcarrier allocation adopts BIP and power allocation is a non-linear programming. A subchannel allocation algorithm is proposed in this thesis as a enhanced solution of ref. [65]. It assigns both InP and VNO subcarriers as many as possible in order o achieve the maximum throughput.

- Heterogeneous wireless networks virtualization

  Apart from the above technologies, ref. [47, 67, 68] study heterogeneous wireless network virtualization. The author in [67] provides a cognitive virtualization platform which enables managing cooperative resources across wired and heterogeneous wireless networks as well as end to end slicing. In addition, this platform allows complete cognitive radio functionalities by virtualizing a cognitive BS. Authors in [68] propose an adaptive virtual network radio resource allocation algorithm based on heterogeneous wireless network virtualization. Ref. [47] introduces an integrated mobile network virtualization by using OpenFlow as well as heterogeneous access technologies.

2.1.4 Business Model of WNV

As mentioned before, WNV not only attracts research but also industries. This subsection provides the business model of WNV. Currently, VNOs impact the traditional role of InPs due to its featured services. Fortunately, WNV benefit both VNOs and InPs [51]. VNOs lease virtual resources from InPs so that VNOs can create their own VNs while InPs gain revenues from resource sharing. Since WNV enables slice isolation, changes or maintenance of one slice will not impact other coexisting VNs. This feature gaurantees VNOs' services requirements. From the VNO's point of view, it can customize its own VNs without the InP's management. Moreover, VNOs can provide more flexible services as well as improve QoS.

In WNV, physical resources and virtual resources are owned by different parties. The business model can indicate different roles in a WNV market. All infrastructure and physical wireless resources such as RANs, transmission networks, backhaul networks, core network, etc. are owned and maintenance by mobile network operators (MNOs) [64]. MNOs virtualize the physical networks into virtual wireless network resources and SPs borrow the virtual resources to create VNs so that they can operate VNs to provide end-to-end services to users. In some works, the MNO refers to InP and SPs refer to VNP and VNO. The roles described above can be further decoupled more specificly in the business model into InP, mobile virtual network provider (MVNP), mobile virtual network operator (MVNO) and SP [19, 51, 69, 70]. There functions are provided below.

- InP: owns all the infrastructure and physical wireless network resources. Responsible for maintaining the physical wireless networks.
- MVNP: leases wireless network resources from InPs and creates virtual resources. A special case shows that MVNPs may have some licensed spectrum so that they can create VNs without requesting spectrum resources from InP.
- MVNO: operates and assigns the virtual resources to SPs [51]. Note that MVNOs may act as both MVNOs and MVNPs. This concept is called everything-is-a-service (XaaS) in cloud computing [71]. While the InP is infrastructure-as-a-service (IaaS) and MVNOs are network-as-a-service (NaaS).
- SP: using virtual resource to provide network services to users which obtains from MVNOs.

In short, virtual resources are based on InPs physically, formed and maintained by MVNPs, managed by MVNOs and used by SPs. It is clear that the four layers of this business model provides more opportunities to the commercial market. It also simplifies each party's responsibility. However, more participants means more coordination and interference which will increase significantly the complexity.

The roles of MVNOs are relatively difficult to identify. Different countries or communities have different definition of MVNOs [72]. As states above, ref. [73] claims that

MVNOs do not have any physical resources such as licensed spectrum and access networks while authors in [72] argue that MVNOs may have infrastructure. The author also describes that MVNOs can break the telecommunication value chain in the future network market.

The business models that are discussed above can be also deployed in IEEE 802.11-based wireless networks [51]. In hot spots data traffic loading, 802.11-based access technologies is an efficient support. Another model based on IEEE 802.11 networks are called testbed-as-a-service (TaaS) [57, 74]. This model is used in the research groups rather than being commercial parties.

2.1.5 Challenges

Although there are a number of advantages of WNV, the research still have to overcome some significant challenges. These challenges need to be addressed before WNV widespread implementation. Some challenges are introduced below and described in detail.

- Isolation: Isolation is considered the basic and essential feature of WNV which enables resource abstraction and sharing across different entities. Any customization, configuration and other changes of a VN would not have impact and interference of other coexisting VNs. Isolation is relatively easy to realize in wired networks. However, due to the unstable characteristic of wireless networks, it is a significant challenge in WNV. In wired networks, virtualization such as spectrum resource abstraction and sharing can be done on a hardware (e.g. links and nodes). While in the wireless communication environment, abstraction and isolation of radio resources is not direct because of random fluctuations inherent to broadcast of wireless communications and radio channel quality properties. Especially in cellular networks, any changes in one cell will cause high interference to neighbouring cells [75]. Furthermore, there are two types of inter cell interference with different cell size. The first interference comes from macro cells overlapping micro cells [5]. The second interference is micro cell overlapping. In addition, the concept of isolation can be introduced to different levels, for example subchannel level, flow level, hardware level [13].

- Control signalling: Before VNs can be created, it is necessary to build the connection between VNOs and InPs so that VNOs can send their requests to InPs. Moreover, a standard language is required to share information among InPs. The VNO also needs connections with its users. Because of the specific features of wireless networks, VNOs might have different QoS requirements. Thus, it is required the control signalling and interface design can be compatible with different QoS requests. Moreover, the control signalling should be implemented among different radio access technologies such as IEEE 802.11 or IEEE 802.16 [51]. In addition, ref. [76] points out that it is sensible to develop standard methods of SP network element programmability. The standardization of control signalling is important to wireless network virtualization.

- Mobility management: Mobility management ensures that the communications can be delivered to users successfully in a wireless network. It also maintains the ongoing traffic with minimum interference while users are moving freely [77]. The mobile management include location management and handoff [3]. Location management delivers communications to users according to their locations. Handoff management ensure the continuous communication by keeping a user connected when moving from one AP to another. In WNV, tracking users' location is relatively difficult because the access VNs ignores the physical networks. In addition, the location information might be own by different VNOs and InPs. Therefore, a centralized location management is possible to solve the problem. On the other hand, the user with ongoing sessions may move among different VNOs or InPs, hence the handoff management is more complicated. To keep the continuous services, a suitable synchronization scheme across different VNs may be considered as a solution.

- Network management: To ensure the usual operation among the WNV services and physical infrastructures, the network management of WNV is crucial. As a virtual network, it is a crossover of multiple physical networks. Hence the network management issues is up against new challenges. In addition, the VNO's requirement may vary dynamically which also bring difficulties to network management. Therefore, the network management should be elastic in order to fit SP's demands. Moreover, the collision of different information and mechanisms that come from multiple parties needs to be avoided. Because a heterogeneous network can be composed by more than one underlying physical network (e.g. macro cells, micro cells, WLAN, etc.) while each physical network has its own special and unique features, it is required the network management has specific protocols for maintenance and operating virtual networks [51].

- Security: Security is a universal problem not only in WNV but also in any type of networks where in WNV, different entities are assumed to be trusted at all times. However, a great amount of intelligent nodes with self context awareness abilities exist in virtual networks may be invalid. In addition, an anonymous party may misbehave within the virtualization mechanism. Hence, new challenges of security are present in WNV.

  The previous knowledge from the traditional wired and wireless networks points out that it is important to present multi-level protections. Regardless of which protection mechanisms is deployed, there are always some weaknesses in the network. To address this problem, authentication is necessary. In addition, a detection-based approach and prevention-based approaches can efficiently identify malicious activities.

2.1.6 Design goals of WNV

Wireless network virtualization can be developed based on a specific business model. There are some design goals that need to be achieved to implement wireless network virtualization. Depending on the scope of the virtualization, these goals can be classified as basic and virtualization specific goals.

1. Basic goals

   (a) Heterogeneity: Since there are many coexisting radio access technologies, wireless network virtualization should allow heterogeneity. And the substrate physical networks should be composed of not only heterogeneous wireless networks but also wired networks. Moreover, the authors of [70] point out that virtual networks on top of them could be heterogeneous (e.g., by using different protocols).

   (b) Scalability: This means InPs must able to scale to support a growing number of coexisting VNs without impacting their performances.

   (c) Stability and convergence: Although isolation ensures that misconfigurations and implementation errors in one VN are contained within itself, the faults and errors that are caused by the underlying physical network may still exist. Virtualization should ensure the stability of the network virtualization environment.

   (d) Mobility: The mobility in WNV not only supports between different InPs but also between VNOs and SPs. That means VNs can geographical mobile at the same time without any disturbing to end users.

   (e) Resource utilization: To use the wireless virtual resources effectively should be guaranteed.

2. Virtualization specific goals

(a) Coexistence: It is clear that coexistence is one of the key characteristics of WNV which allows multiple individual virtual entities coexist on the same physical infrastructure [70]. In addition, virtual networks are sliced according to the VNOs' requests, thus the differences between virtual slices are allowed to exist.

(b) Flexibility: By means of decoupling controllers from the underlying physical networks, the flexibility of each virtual entity is provided by the WNV [2]. Notice that the flexibility not only be enabled between physical and virtual networks, but also across coexisting virtual networks. Moreover, virtualization can be applied in different levels such as flow level, subchannel level or even physical level. The flexibility of virtualization in lower level has more freedom, it is more efficiency to enables VNs isolation as well as resource customization flexibility in lower level. But the disadvantage is the complexity of implementation while flexibility on higher levels has the opposite effect.

(c) Manageability: Due to the virtual networks are assigned to VNOs and the virtual networks are completed decoupled from the physical networks, WNV needs to offer a full end-to-end control to VNs to VNOs [2]. The network manageability enables VNOs to manage their own VNs without telling physical substrate.

(d) Isolation: To improve fault tolerance, security and privacy, isolation between coexisting VN is necessary. It must make sure the faults in one VN do not affect other coexisting VNs. In WNV, multiple VNs come from the same substrate but transparent to each other. One virtual slice should be invisible to another. Thus the changes such as changing protocols, configurations, and customization will not have impact to other coexisting VNs. The isolation is the basic goal on WNV design. Without isolation, the WNV is hardly achieved. However, due to the unstable features of wireless communication, it becomes a challenge on WNV.

2.2 WNV performance factors

2.2.1 Traditional Wireless Networks Performance Factors

In traditional wireless networks, several metrics are used to measure the performances of a network. It is clearly that these metrics can also be used to evaluate wireless network virtualization.

- Costs: Costs means the total investment of wireless network operators which includes CapEx and OpEx [3]. In cellular networks, the CapEx includes building up BS and transmission towers, antennas and equipment installation. In contrast, OpEx consists of maintenance charge, equipment lease, operation power charge [78]. In WNV, InPs are responsible for the majority of the deployment costs while OpEx may be charged by both InPs and VNOs.
- Revenue: One of the main purposes of WNV is to generate more revenues than traditional networks. The concept of profit is used to assess the value of WNV. In addition, the revenue to cost ratio (RCR) is another measurement [51]. InP and VNOs are more attempted to deploy WNV mechanisms with higher profit or RCR values.
- Deployment efficiency: According to [78], deployment efficiency is used to assess the network coverage and deployment costs ratio. The deployment efficiency usually needs to be estimated by network engineers when deploying networks.

- Spectrum efficiency: Similar to the previous metric, spectrum efficiency is used to measure the ratio between system coverage and spectrum. It is especially important to cellular networks optimization. In addition, some detailed spectrum efficiency metrics are used to assess WNV performance, for example the cell edge spectrum efficiency [78].
- Energy efficiency: Energy efficiency (EE) is the ratio between system throughput and energy consumption. The energy consumption includes the overall network energy consumption [79]. This thesis provides an algorithm which aims to maximize the overall EE by means of power allocation.
- QoS: QoS can be defined into several terms, such as data rate, packet delay and packet loss rate [80]. Usually, the end users specify the QoS requirement. In this thesis, all proposed algorithms consider InPs' QoS requirements in terms of data rate. The algorithms all guarantee the users' traffic data rate from InPs.

2.2.2 WNV Specific Factors

This subsection introduces some virtualization specific metrics which is particular for assessing the performance of virtual wireless networks.

- Throughput between virtual entities: The throughput between different virtual entities can be used to evaluate the connection between virtual nodes to end users. This is different from the traditional throughput in which the virtualization specific throughput is the average data rate that achieved by virtual entities [51].
- Isolation level: It is can be observed that the isolation is significant important in WNV. To evaluate the quality of the VN, isolation should be always considered. To be noticed that, isolation can be implemented in different levels from a range of physical level to software level.

2.3 Wireless Virtual Resource Allocation

This section discusses the important research issue of WNV including network sharing, virtual resource discover and resource allocation. Network sharing is the key feature of WNV because the virtualization is achieved by network sharing. To improve the resource utilities, first it needs to discover all virtual resources. Then the resource allocation algorithm can be proposed.

2.3.1 Network Sharing

As mentioned before, one of the most important features of WNV is resource sharing. By means of resource sharing, the resource utilities can be improved. The following introduces several types of resources sharing.

- Spectrum sharing: Spectrum sharing is defined as multiple network operators having an agreement that allows the licensed frequency band own by them to be shared. For instance, NO_1 and NO_2 have an agreement that any of them can use each other's resources. By this agreement, both NOs have more flexibility on spectrum scheduling as well as on improving the networks' performances. The cross operators spectrum sharing has been introduced decades ago [81, 82]. Because of WNV, the spectrum sharing is considered again so that it can provide full virtualization to the networks.

- Infrastructure sharing: In this case, the infrastructure is the only resource that is being shared. It is possible to deploy WNV across different InPs or within an InP where virtualization based infrastructure sharing can be called cross-infrastructure virtualization [73]. Authors in [83] introduce a passive sharing and an active sharing of infrastructure. Passive infrastructure sharing is defined to share building permission and sites. Recently, some third parties are responsible to provide passive RAN infrastructure sharing. The active sharing enables the sharing of whole network elements sharing, including antennas, eNodeBs, backhaul networks, routers, etc.

A multioperator RAN is proposed for network sharing in [84]. This architecture enables multiple InPs sharing RANs. 3GPP provides two environments that the infrastructure sharing can be used [80]. The first one is that InPs access to the shared RAN directly and offer services using their own spectrum. The second one is in a geographically split basis, in which InPs cover a specific area of a country with their own spectrum and get together to provide network coverage over the entire country. This environment has a typical use which is known as national roaming.

- Full network sharing: Full network sharing consists of spectrum and infrastructure sharing. Namely both spectrum resources and infrastructure can be shared by multiple InPs at the same time. 3GPP specification provides three scenarios of full network sharing. The first scenario allows a part of operators to access to the RAN while the specific geographical area is hosted by a third-party [80]. In the second scenario, one or more InPs share their licensed spectrum together. The licensed spectrum can be gather into a spectrum pool and is shared by all InPs. This is realised by introducing a radio network controller. The controller connects all operators to the shared RAN or in another case, all operators are connected together then the controller enables access to the shared RANs. The last scenario allows different RANs share a common network, where the RANs belong to different operators. The proposed scenarios provide more flexibility and efficiency to the physical substrate networks by means of full network sharing. To sum up, full network virtualization results in the universal virtualization where virtualization can exist everywhere [73].

2.3.2 Virtual Resource Discovery

Resources in a wireless network is limited. Hence by deploying WNV, the InP and VNOs should discover the maximum available resources from the physical networks. The InP has to determine the amount of resources which is used for virtualization. Namely, the InP reserves resources for its own users. A coordination mechanism is required because of the resource sharing across different InPs. In addition, virtual resources need to be discovered in VNOs. Hence a specific communication protocol is deployed between InPs and VNOs. Furthermore, naming and addressing issues enable the initialization process of recognizing physical links and nodes which is also important in resource discovery. Users are able to connect to multiple VNs, and VNOs are allowed to aggregate resources from different InPs [85]. Thus, a well designed global naming and addressing policy is required for distinguishing physical entities and virtual entities.

Generally speaking, radio spectrum resources are licensed spectrum or in some special case the radio resources are free (e.g. WiFi and WiMAX), which is important for wireless transmission. As in cognitive radio, the available radio resources expands from a special range to white spectrum, which allows more resources can be used in wireless transmission [86].

Due to the development and improvement of network sharing, CRNs and heterogeneous networks deployment (such as micro cells and femtocells) [72, 87, 88], the radio spectrum has been decoupled as a single element of WNV. Compared to the current spectrum access, CR technology enables more flexibility of spectrum usage. Moreover, the heterogeneous networks allows reuse of licensed frequency band.

Wireless network infrastructure and spectrum can be sliced into a set of virtual slices where these slices are combined as wireless virtual resources. A standardized slice consists of all virtual elements in the wireless network infrastructure. Namely a complete slice can be seen as a typical wireless VN. For example, a slice that is requested by a VNO is able to deploy all virtual elements in this slice. However, the ideal slice is difficult to create. Thus the InP only guarantees some QoS requirements of VNOs' users.

2.3.3 Resource Allocation Algorithms

This subsection introduces different resource allocation algorithms, including resource allocation under different backgrounds, using different mathematical tools etc. In addition, the work in this thesis is used to compare with others. Three main research topics in network virtualization are isolation, embedding and resource allocation. There only a few studies in the WNV isolation. Ref. [7] and [8] study virtual network embedding in mesh networks. The authors in [12] take online requests into account when proposing the embedding algorithm. Kokku et al. focus on effective wireless resources virtualization as well as admission control of WiMAX [13]. Ref. [13] considers both uplink and downlink resources while [63] supports downlink well. An efficient resource allocation algorithm for WNV using time and space division is provided in [89]. The authors are more concern about VN topology. Although a higher resource utilization is achieved, QoS has not been considered in this algorithm. The thesis proposed three algorihms with data rate requirement constraint. Checco and Leith establish a max-min fair flow rate allocation in TDMA-based mesh network [90].

There is much more work done on resource virtualization algorithms in wired networks. Ref. [2] states that resource allocation in WNV including allocating virtual links and virtual nodes, either statically or dynamically on the physical paths or nodes. Because of the limitation of wireless communication, it is more difficult to study in a wireless system rather than a wired. However, authors in [91] present a general model of the fibre-wireless (FiWi) access network virtualization that combines a fiber network and a wireless network. To achieve FiWi network's seamless networking is complicated.

Thus, FiWi virtualization does not consider the differences between fiber networks and wireless networks.

An adaptive virtual network radio resource allocation (VRRA) algorithm is proposed in ref. [68]. This algorithm is deployed after an resource allocation initialization. In addition, the algorithm also can reallocate resource dynamically in order to meet the minimum requirement of the virtual BSs. The requirements of VNs introduced in VRRA algorithm refers to transmission rate,error rate and delay.

There are some work studies on resource allocation of virtual networks using game theory [92–94]. The author in [94] proposes a non-cooperative game model on the bandwidth capacity allocation algorithm. This algorithm is introduced to find out the bandwidth allocation scheme by Nash equilibrium (NE). However, the author considered the bandwidth as the radio resource. Thus there is no capacity and radio resource relationship shown in that piece of work. Compared to this algorithm, this thesis applying a non-cooperative game model to a power allocation algorithm. This algorithm considers power as the allocated resources, it also provides how the power changes affect the capacity. Authors in [92, 93] abstract the resources into the data rate manner which is calculated as a group of data rate that can be achieved with spectrum allocation. Furthermore, an auction approach of network resources are provided sequentially to VNOs. Because the dynamic requirement is considered in this approach, this auction is modelled into a stochastic game. The efficient data rate allocation scheme can be obtained by finding the NE of this stochastic game.

Another promising way to study resource allocation is network embedding. Ref. [74, 95, 96] use frequency-division multiplexing (FDM) to embed wireless link virtualization, and the virtual transmission media can be isolated in the frequency domain. The ORBIT test-bed was chosen as the experiments platform by authors in ref. [95] and [96]. An operating system (OS) that can support user mode Linux OS is running on a hardware that is considered as the VM, which ensures the hardware virtualization. In contrast, the authors in ref. [96] prefer running multiple OSs on the physical hardware. No matter which OS is running on the hardware, it is required to have the ability of schedule resources for the VMs. The authors in ref. [74] expand previous work where a novel test-bed is proposed to move telecommunication as a services (TaaS) to a wireless cloud. In addition, the work in [74] uses and expands a resource specific language for the wireless virtualization experiments.

Another multiplexing technology time-division multiplexing (TDM) is used to study wireless link virtualization in ref. [55, 56]. The TDM separates the physical network in the time domain into different VNs. Thus the experiments or traffic loads of VNOs are isolated to each other on the time domain basis. the virtualization mechanisms in ref. [56] has been implemented on a large-scale IEEE 802.11 wireless test-bed equipment where authors in ref. [55] assess the TDM-based link virtualization via delay, network utilities, jitter, etc. Different from ref. [56] and [55], the authors in [57] propose an space-division multiplexing (SDM)-based IEEE 802.11 experiment network to embed virtual links which is called ORBIT. The comparison of the isolation between TDM and SDM is evaluated where SDM performs better.

A resource allocation mechanism has to determine how to embed a wireless VN on the physical networks [51]. Namely which links and nodes should be decided or what factors need to be optimized [97]. Authors in ref. [98] find out that embedding virtual network with QoS requirements can turn into an NP-hard optimization problem, and the authors provide the solution on how to embed virtual networks. The survey [14] provides details information of virtual network embedding. A typical tool used for researching embedding problem is Karnaugh-map. In ref. [12] the authors use it to handle the online traffic of WNV and embed VNs dynamically. Ref. [53, 99] presents a new architecture that the VNs are split according to users' requirements such as mobility, security, flexibility requirements. A specific virtual network is shared by a group of similar context requirement users.

Admission control is another important research topic in resource allocation. The admission control is resposible to manage the new incoming users. The purpose of implementing admission control is to guarantee the current users' QoS as well as maximizing the resource utilities. In the VNO's admission control, it should estimate the requested virtual resources and ensure such amount of resource is less than the physical network capacity. Ref. [100] and [101] state that both virtual demands (nodes, links) and physical capacities (nodes, links) are considered. However, the work only copes with network topology, it does not consider admission control as there is no virtual links or nodes requests.

Mobile network virtualization (MNV) has emerged as flexible and efficient solution to enable applying customized services on a shared infrastructure [51]. Numerous work studies the resources allocation algorithm in wired network virtualization. However, the limitation of wireless communication brings more difficulties to MNV research. The author in ref. [63] presents a virtual base station framework for WiMAX which could be deployed on both test-bed and mobile network operators. Ref. [92] presents a MNV framework to support multiple heterogeneous networks (HetNets) services over the same physical network. Similarly, ref. [102–104] study the resources allocation problem on HetNets. It is known that the HetNets also allows resources sharing, however the proposed algorithm in this paper is on an OFDMA-based LTE-A MNV which is widely implemented in nowadays telecommunication system.

Ref. [105] considers HetNets into account when studies resources allocation on a single-input-single-output (SISO) MNV transmission system. The author maximizes the aggregate utility in terms of the revenue of VNOs. Although the simulation results shows that the performance of utility and capacity are improved, the SISO transmission system is not deployed generally. Similarly, the author in [106] formulates the virtual resource allocation as an optimization problem which maximizes the VNOs' utility. In addition, it also proposed an information-centric wireless network (ICN) virtualization framework for enabling both MNV and ICN.

Ref. [36] provides a resource management algorithm to the LTE virtualization. The authors measure resources in PRB bases. This algorithm enhances the overall network performance and resource efficiency. For example, the end-to-end delay decreases dramatically with virtualization. In addition, the throughput increases with the number of VNOs growing. However, one VNO is assigned fixed resources while others share the rest. Thus, this algorithm does not provide fully resource flexibility across VNOs. Liu and Tian propose a dynamic resource allocation algorithm with the consideration of fairness for LTE which the resources are also measured by PRBs [43]. The expectation index in terms of VNO's satisfaction is evaluated. Although the fairness can be achieved across VNOs, the requirement of all VNOs cannot be satisfied, this is the algorithm's weakness. Lu et al. propose an elastic resource virtualization algorithm (ERVA) in [65]. It minimizes the throughput of VNOs and maximizes the throughput of InPs. The disadvantage of ERVA is requests from VNOs cannot be satisfied if they exceed the service level agreement (SLA). Moreover, introducing different strategies to the InP and VNOs may complicate the algorithm. In contrast, this thesis proposed an evolved-ERVA (E-ERVA) that is more elastic algorithm than ERVA. It allows either VNOs or InPs use the spare resource where ERVA only allows the InP to use it. Thus, E-ERVA achieves higher throughput and resource utilization than ERVA. In addition, E-ERVA maximizes the throughputs of InP and VOs which reduces the complexity of the algorithm.

In WNV research area, resource allocation is the process of reserving and allocating physical resources to elements such as virtual nodes and virtual links. There are several differences of resource allocation in other networking paradigms such as virtual private networks (VPNs) [107]. First, the topology of a VN is arbitrary. Second, resource allocation for VNs has to consider traffic balancing for both physical links and physical nodes. Third, sources and destination of connections are unknown in advance. Currently, most of the research and techniques are based on heuristic methods. However, the exact solutions of WNV is rarely applied. The challenge is to develop efficient formulations of the allocation problem that can be used to resolve the largest possible instances of the problem in reasonable time.

An alternative approach to tackle the resource sharing problem in wireless transmission system based on an economic model has been presented in ref. [108, 109]. In this model, a utility function is introduced as a measurement of each player's level of satisfaction achieved from using the system resources [110]. A game theory based solution to the resource sharing problem is presented in this paper. Game theory is commonly used in microeconomics. It is an efficient tool in modelling interactions between self-interest players and predicting their preference of strategies [111], [112]. Each player in the game intends to maximizes some functions of utility in a distributed manner. Due to the players acting selfishly, the equilibrium point is not the best operating point.

Pricing-based resource allocation algorithm is generally adopted in cognitive radio networks (CRNs) [113–115]. However, a few works research WNV resource allocation that is based on the consideration of price. This thesis considers a WNV transmission system that several VNOs can improve their utilities by sharing the spare power from an InP. The VNO's strategy selection is formulated as a non-cooperative game which bases on the price information that is provided by the InP. Take this price information into account, the InP adjusts the size of the allocated power to VNOs while the adjust speed is controlled by a learning rate. Since each VNO aims to maximize its own utility, there exists an equilibrium point which enables no VNO to improve its utility by adopting a different strategy. To sum up, the purpose of the power allocation game is to find out the equilibrium point that can maximize each VNO's utility via the InP's power allocation.

Some authors focus on the energy efficiency (EE) on resource allocation based on OFDMA transmission system. For example, a downlink resource allocation algorithm for multi-users in wireless transmission system is studied in [116]. The author proposes an algorithm which take the minimum required transmission rate, minimum required power and the circuit power consumption into account when formulate the energy efficiency optimization problem. The evaluation results show that the presented algorithm converges fast. In addition, the system capacity and energy efficiency profit by having multiple users. However, the optimization problem of this algorithm is non-convex. Thus, the author presents a novel iterative solution by means of non-linear fractional programming and Lagrange dual decomposition.

In ref. [117], the author investigates an energy efficient resource allocation for a single input single output (SISO) downlink communication system. The maximum EE power allocation problem is non-convex. The problem is then turned into a quasi-convex optimization problem and the author converts this optimization problem into two sub-problems in order to find out a solution. Ref. [118] proposes an EE multi resource allocation scheme for OFDMA CRNs with multiple secondary transmitters. A joint subcarriers and power allocation algorithm is presented as the best strategy of secondary transmitters. In ref. [119], the impact of cell sizes on energy efficiency in cellular networks has been studied. The work shows that the energy efficiency increased by reducing the cell size. Moreover, EE can be further enhanced by implying a sleep mode. Ref. [120] develops an uplink pilot and downlink adaptation approach to improve the energy efficiency in a time division dual (TDD) based multi-user multi-input and multi-output (MIMO) system where the downlink transmission is based on the uplink channel estimation. While in ref. [121], the author focuses on the EE design in MIMO-OFDM downlink system and with consideration of users' QoS grantees. Similar to ref. [121], this thesis provides a MIMO-OFDMA downlink system. However, the QoS requirement only refers to data rate in this thesis. On the other hand, ref. [122] investigates the trade-off between the energy efficiency and spectral efficiency in a downlink MIMO-OFDMA system. Ref. [123] studies a power control game in order to achieve end users' specified signal to interference ration targets with minimum transmitted power in multiple antenna systems.

The following chapters proposed three resource allocation algorithms including sub-channel allocation, power allocation and joint resource allocation algorithms. Each algorithm has different objective, however they provide a guidance to InPs and VNOs in choosing suitable algorithms. In another words, the InP can deploy a specific according to VNOs requirements. The resource allocation algorithms proposed in this thesis give a good opportunity for InPs and VNOs to achieve different purposes.

Chapter 3

Subchannel Allocation Algorithm

This chapter proposes a subchannel allocation algorithm for WNV transmission systems with QoS consideration. This algorithm specifyies data rate as the QoS requirement. It aims to find out the maximum throughput of both InP and VNOs. The simulation is based on one InP with multiple VNOs system model. However, the algorithm is compatible with other WNV structures. This algorithm is called evolved elastic resource virtualization algorithm (E-ERVA).

The algorithm is based on an OFDMA transmission system, thus the basic concept of OFDMA is introduced first. Then the system is modelled as a binary integer optimization problem and a QoS aware subchannel allocation algorithm is proposed. Finally, an evaluation is presented and analysed. This work has been peer reviewed and published on *2014 International Conference on Multimedia Communication and Computing Application* [124].

3.1 System Model

3.1.1 Brief introduction of OFDMA

The key idea of OFDMA is to divide a carrier into a number of orthogonal subchannels, split high data rate flow into several low data rate flows, then module low data rate flows onto the orthogonal subchannels. These orthogonal subchannels reduce inter-carrier interference. A typical LTE transmission system is based on OFDMA resources block for downlink. FIGURE 3.1 displays a typical downlink PRB. The space between two subchannels is 15 kHz with a total frequency range at 180 kHz of each block. In the time domain, each subchannel contains 7 symbols with 0.5 ms in total. Therefore, an OFDMA block contains 12 subchannel $\times$ 7 symbols = 84 elements. Each element carries QPSK, 16QAM or 64QAM modulated bits which depends on channel conditions. In short, the more resources blocks a user receives, the higher bit rate it can obtain.

The research is based on a perfect channel information assumption on both transmitter and receiver. However, it is rarely possible to have such perfect transmission environment, especially in wireless communication systems. For instance, the wireless channel random fading is one of the serious problems that need to be considered while applying a resource allocation scheme. Furthermore, slice isolation is also important when a dynamic resource allocation algorithm is applied to virtual networks.

E-ERVA specifies VNs that are operated by the InP, which are called *local* slice, while *foreign* slices represent the VNs that are operated by VNOs. In addition, E-ERVA bases on an OFDMA system. Hence, the resource allocation problem can be converted to allocate PRB to both local and foreign slices in order to achieve maximum throughput. This section illustrates the problem statement in detail.

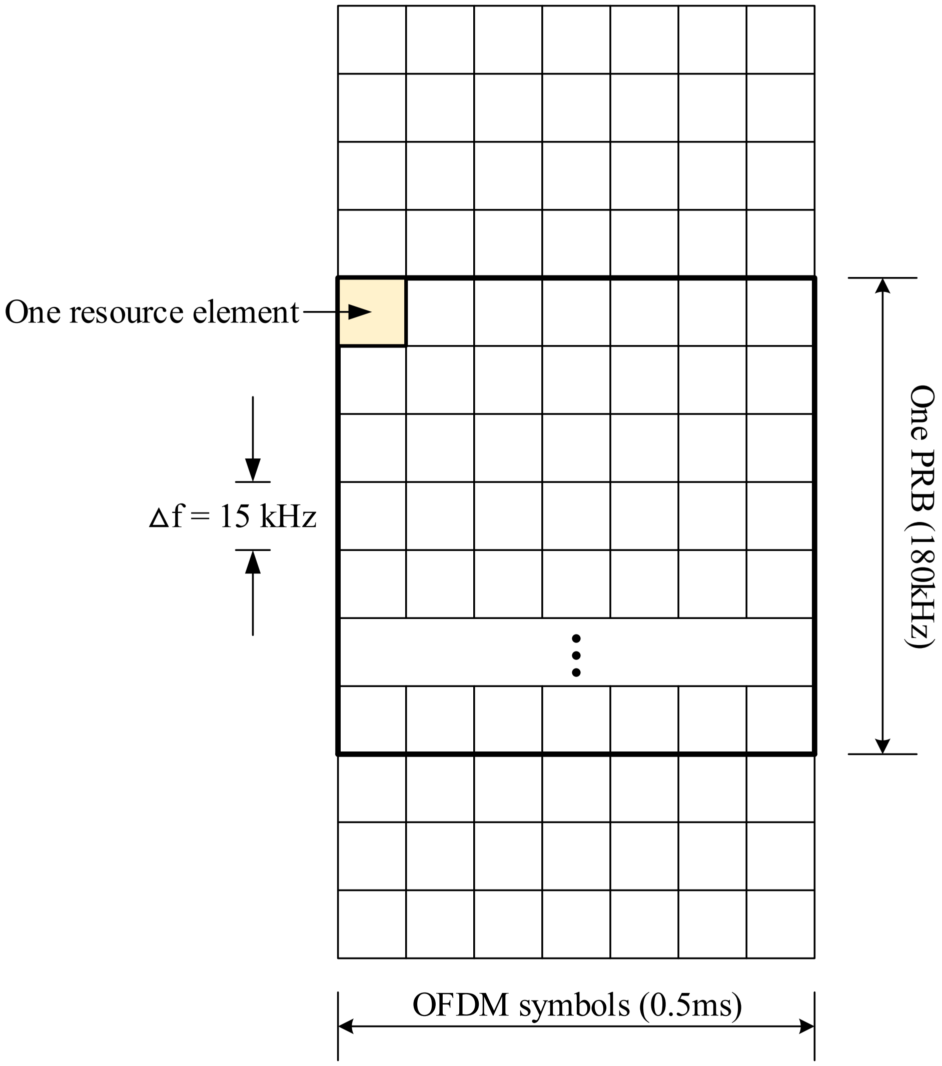

FIGURE 3.1: Physical Resource Block

3.1.2 Problem Description

Resource allocation algorithms are categorised into margin adaptive (MA), which minimizes the total transmit power with the constraint on users' requests; and rate adaptive (RA) that maximizes the total throughput with the constraints on transmit power as well as users' requests [125] where E-ERVA is based on RA. Each user experiences different channels, thus every PRB has different data rate that is seen by different users.

E-ERVA considers a multi-user OFDMA system with K users. The K-th user may produce f traffic flows and each flow will be assigned a set of subchannels. Thus each flow can specify its own QoS requirements. Furthermore, the instantaneous channel information on all subchannels of all flows are known by the transmitter. Therefore, the transmitter is able to apply the allocation algorithm to assign different subchannels to the flow according to the channel information. Table 3.1 indicates the major notations used in E-ERVA.

TABLE 3.1: Notations

B	Total bandwidth of the system
N_0	Noise power spectral density
C	Number of system subchannels
F	Number of flows
M	Number of foreign slices
A	Subchannels set
φ_i	SLA
$r_{f,c}$	Allocate c-th subchannels to f-th flow
$r_{req_{f,S_i}}$	Request from f-th flow in slice i
$p_{f,c}$	Power allocated to c-th subchannels in f-th flow
$h_{f,c}$	Channel gain of c-th subchannels in f-th flow
$I_{f,c}$	Assignment index indicating f-th flow occupies c-th subchannels
$BER_{f,c}$	Bit error rate (BER) of c-th subchannels in f-th flow

One subchannel cannot be shared by more than one flow, for each c if $r_{f',c} \neq 0$, $r_{f,c} = 0$ for all $f' \neq f$. In the frequency selective fading channel, different subchannels experience different channel gains. If M-ary quadrature amplitude modulation (MQAM) is employed, the BER for an additive white Gaussian noise (AWGN) channel can be given by Eq. (3.1) [126].

$$BER_{f,c} \approx 0.2exp\left(-\frac{1.5p_{f,c}h_{f,c}^2}{(2^r-1)\,N_0\frac{B}{C}}\right) \tag{3.1}$$

Thus, in order to maintain the required QoS at the receiver, the transmit rate of f-th flow that allocates the c-th subchannel is:

$$r_{f,c} = \frac{B}{C} log_2 \left(1 - \frac{1.5 p_{f,c} h_{f,c}^2}{ln(5BER_{f,c}) N_0 \frac{B}{C}} \right) \tag{3.2}$$

The purpose of E-ERVA is to find the best assignment of $r_{f,c}$ so that the sum of it is maximized for a given transmission power and QoS constraints. In order to make the problem tractable, no power is needed if no bits are transmitted.

3.2 Proposed Subchannel Allocation Algorithm

Foreign slices can be denoted as Slice 1 to M (i.e. S_1 to S_M) where the local slice is represented by S_0 in particular. In order to improve the resource utilization, throughput of both local and foreign slices should be maximized. Hence the problem can be converted to an optimization problem that allocate subchannels to the local and foreign slices with the QoS constraint. Mathematically, the problem can be formulated as Eq. (3.3).

$$max \sum_{f=1}^{F} \sum_{c=1}^{C} r_{f,c} I_{f,c} \tag{3.3}$$

s.t.

$$C1: \quad \sum_{f=1}^{F} I_{f,c} = 1$$

$$C2: \quad \sum_{c=1}^{C} I_{f,c} \geq 1$$

$$C3: \quad I_{f,c} = \{0, 1\}$$

$$C4: \quad \sum_{c=1}^{C} r_{f,c} \geq r_{req_f}$$

$$C5: \left(\sum_{i=1}^{M} r_{req_{f,S_i}} \leq \sum_{i=1}^{M} \varphi_i\right) \ or \ \left(\sum_{f \in S_0} r_{req_{f,S_0}} \leq B - \sum_{i=1}^{M} \varphi_i\right)$$

In the formulation description, C denotes constraints that are presented to slices. $C1$ describes that each subchannel is occupied by only one flow at any time slot while $C2$ illustrates that f-th flow can be assigned to more than one subchannel. $C3$ specifies the c-th subchannel is occupied by f-th flow (value 1) or not (value 0). $C4$ ensures the allocated subchannels satisfy the requests from f-th flow in S_i. Finally, $C5$ provides a *pay as you use* model to foreign slices which is illustrated below.

There are four cases under constraints $C5$:

- Case1: $req_f \leq SLA, req_l \leq Upp$
- Case2: $req_f \leq SLA, req_l \geq Upp$
- Case3: $req_f \geq SLA, req_l \leq Upp$
- Case4: $req_f \geq SLA, req_l \geq Upp$

Upp refers to the upper limit of the local slice (i.e. $B - \sum_{i=1}^{M} \varphi_i$). Namely the total bandwidth B minus the total bandwidth that are used by foreign slices i to M is the available bandwidth for local slice. For Case1, both req_f (requests from foreign slices) and req_l (requests from local slice) can be satisfied. For Case4, the sum of req_f and req_l are greater than the total amount of resources, thus both of them cannot be satisfied and the resources are fully used. Case2 and case3 are two aspects which is being mainly concerned. Case2 describes when req_f is satisfied but not over the SLA, then req_l occupies the rest of resources regardless of Upp. In case3, req_l is less than the Upp while req_f is greater than SLA. Therefore, req_l is fully satisfied and req_f can take the residual resources without considering SLA. $C5$ covers case2 and case3: either req_f or req_l is satisfied. That Upp represents the service agremment between the local slice and foreign slices: in the extreme situation when the network is overloaded, foreign slices are still able to provide services and the local slice cannot violate the agreement. In other cases, either the local slice or foreign slices have spare resources, it will be shared by other slices. This is how the algorithm achieve elastic.

The achieved data rate of each subchannel depends on the subchannel quality. One subchannel has different transmission rate by assigning different flows, it is because channel gains of each subchannel are various. Thus a cost matrix of $r_{f,c}$ can be written as:

$$R = \begin{bmatrix} r_{1,1} & r_{1,2} & \cdots & r_{1,c} \\ r_{2,1} & r_{2,2} & \cdots & r_{2,c} \\ \vdots & \vdots & \ddots & \vdots \\ r_{f,1} & r_{f,2} & \cdots & r_{f,c} \end{bmatrix} \tag{3.4}$$

and assignment index $I_{f,c}$ is:

$$I = \begin{bmatrix} I_{1,1} & I_{1,2} & \cdots & I_{1,c} \\ I_{2,1} & I_{2,2} & \cdots & I_{2,c} \\ \vdots & \vdots & \ddots & \vdots \\ I_{f,1} & I_{f,2} & \cdots & I_{f,c} \end{bmatrix} \tag{3.5}$$

then the optimization problem can be rewritten as $max\, R \cdot I$, that is:

$$max\, R \cdot I = \begin{bmatrix} r_{1,1}I_{1,1} & r_{1,2}I_{1,2} & \cdots & r_{1,c}I_{1,c} \\ r_{2,1}I_{2,1} & r_{2,2}I_{2,2} & \cdots & r_{2,c}I_{2,c} \\ \vdots & \vdots & \ddots & \vdots \\ r_{f,1}I_{f,1} & r_{f,2}I_{f,2} & \cdots & r_{f,c}I_{f,c} \end{bmatrix} \tag{3.6}$$

The optimization problem in (3.3) is a typical binary integer programming (BIP) problem. BIP is a special case of integer programming that variables are required to be 0 or 1. A linear programming based branch-and-bound method is used to solve the BIP. The form of *BIP* is:

$$max\ \ \mathbf{q}^T\mathbf{x} \tag{3.7}$$

s.t.

$$\mathbf{A} \cdot \mathbf{x} \geq \mathbf{b}$$

$$\mathbf{Aeq} \cdot \mathbf{x} = \mathbf{beq}$$

$$x_i = \{0, 1\} \quad i = 1, 2 \cdots n$$

where x is the solution variable vector which represents the element is assigned or not, i.e. $I_{f,c}$ in E-ERVA. $\mathbf{q^T}$ is weight vector for assignment (i.e. R). **Aeq** and **A** are equality and inequality constraint matrix respectively while **beq** and **b** are equality and inequality limits vector respectively. Consequently, the optimization problem that expresses in (3.3) can be solved by BIP. The E-ERVA is proposed in the following.

Each slice contains several flows. This algorithm first calculates the achieved data rate of each flow with assigning different subchannels. For example, flow 1 has the data rate of $r_{1,1}$ if subchannel 1 is assigned and it has the data rate of $r_{1,2}$ if subchannel 2 is assigned. Followed by, the assignment index $I_{f,c}$ is introduced. When $I_{f,c}$ equals 1, the

Algorithm 1 Evolved Elastic Resource Virtualization Allocation Algorithm (E-ERVA)

Input: $M,\ r_{req_{f,S_i}},\ \varphi_i$

for $f \in S_i,\ c \in A$ **do**

  $r_{f,c} = \frac{B}{C} log_2 \left(1 - \frac{1.5 P_{f,c} h_{fc}^2}{ln(5BER_{f,c}) N_0 \frac{B}{C}}\right)$

  $x_i = I_{f,c}$

  $q_i = r_{f,c}$

  $A = r_{req_{f,S_i}}$

  $Aeq = \sum_{f=1}^{F} I_{f,c}$

end for

if satisfy

  $\left(\sum_{i=1}^{M} r_{req_{f,c}} \leq \sum_{i=1}^{M} \varphi_i\right) or \left(\sum_{f \in S_0} r_{req_{f,c}} \leq B - \sum_{i=1}^{M} \varphi_i\right)$ **then**

  Solve **BIP** by branch-and-bound method

else

  $\sum_{i=1}^{M} r_{f,S_i} + r_{f,S_0} = B$

end if

c-th subchannel is assigned to f-th flow. On the other hand, if $I_{f,c}$ equals 0, it means the c-th subchannel is not assigned to f-th flow. Then the data rate and assinment index matrixes are formed. With the condition that mentioned in C5, the optimization problem is solved by branch and bound method. Finally, the maximum data rate is calculated.

3.3 Performance Evaluation

This section shows the simulation results of E-ERVA. The simulation is based on MATLAB and a fully isolation is provided across local and foreign slices. For comparison, a static resources virtualization algorithm (SRVA) is provided which means assigning the same amount of resources to foreign slices as requests in the SLA regardless of the real-time traffic from the particular slices while E-ERVA considers the real-time traffic demands when allocating resource to slices.

The throughput is measured from the InP's side rather than individual slices. E-ERVA attempts to increase the throughput of the whole physical network while satisfying the bandwidth requests from an individual flow of different slices.

According to the LTE standard, the bandwidths can be chosen from 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz and 20 MHz [80]. The total bandwidth is set to 1.4 MHz in this simulation. To simplify the calculation, three slices are simulated that include one local slice and two foreign slices. In addition, each foreign slice contains two flows and the local slice contains four flows. The traffic load follow a Poisson distributed model for all flows.

FIGURE 3.2 shows the effects of different resource allocation schemes across foreign and local slices when the overall channel capacity varies due to the change of SNR. The SNR value is 15dB for the OFDM frame number from 0 to 300 and 20dB for number of 301 to 600. It can be observed that the throughput increases as SNR gets better. This is because the channel capability raises with higher SNR. However, E-ERVA outperforms remarkably compare to SRVA.

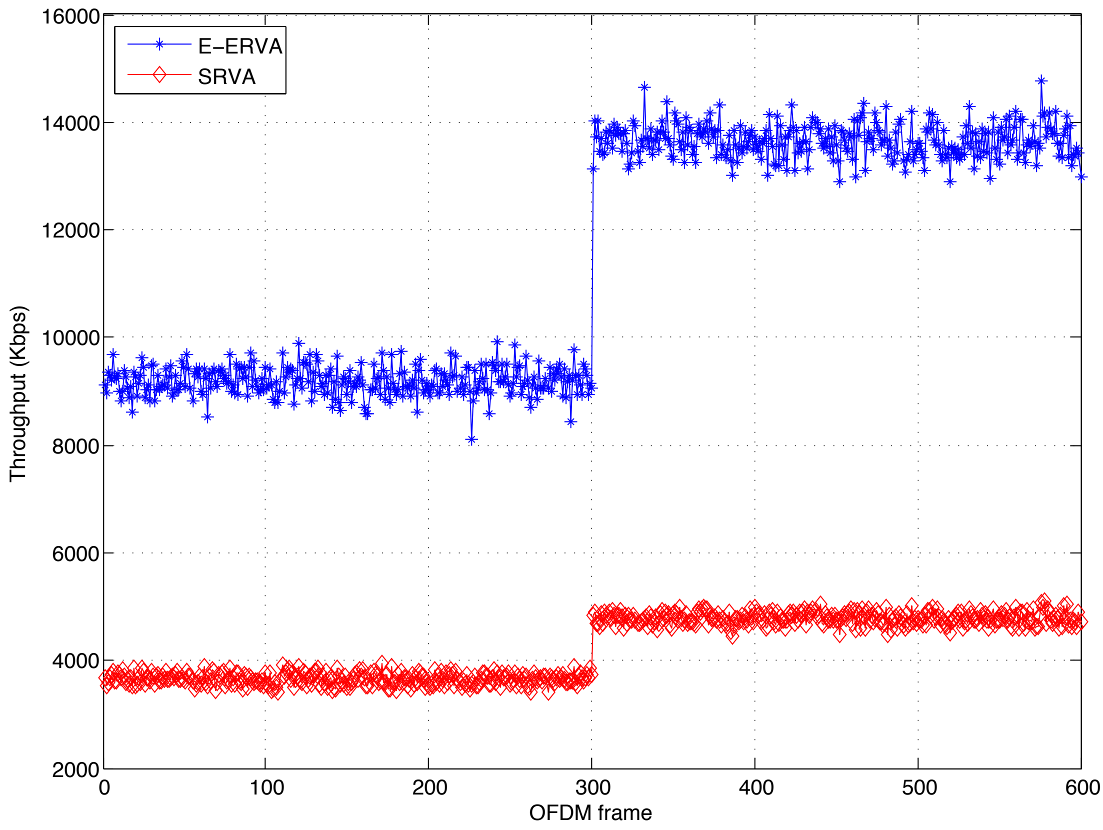

FIGURE 3.2: Throughput with different SNR

In FIGURE 3.3, the throughput of E-ERVA and SRVA with different BER are evaluated. OFDM frame number 0 to 200 evaluate BER at 10^{-5}, number 201 to 400 evaluated BER at 10^{-6} and 10^{-7} of the last 200 frames. It can be seen that throughput decreases as the BER decreasing for both algorithms. The reason is that in order to guarantee the received data rate, more bits are required to transmit when the BER is high.

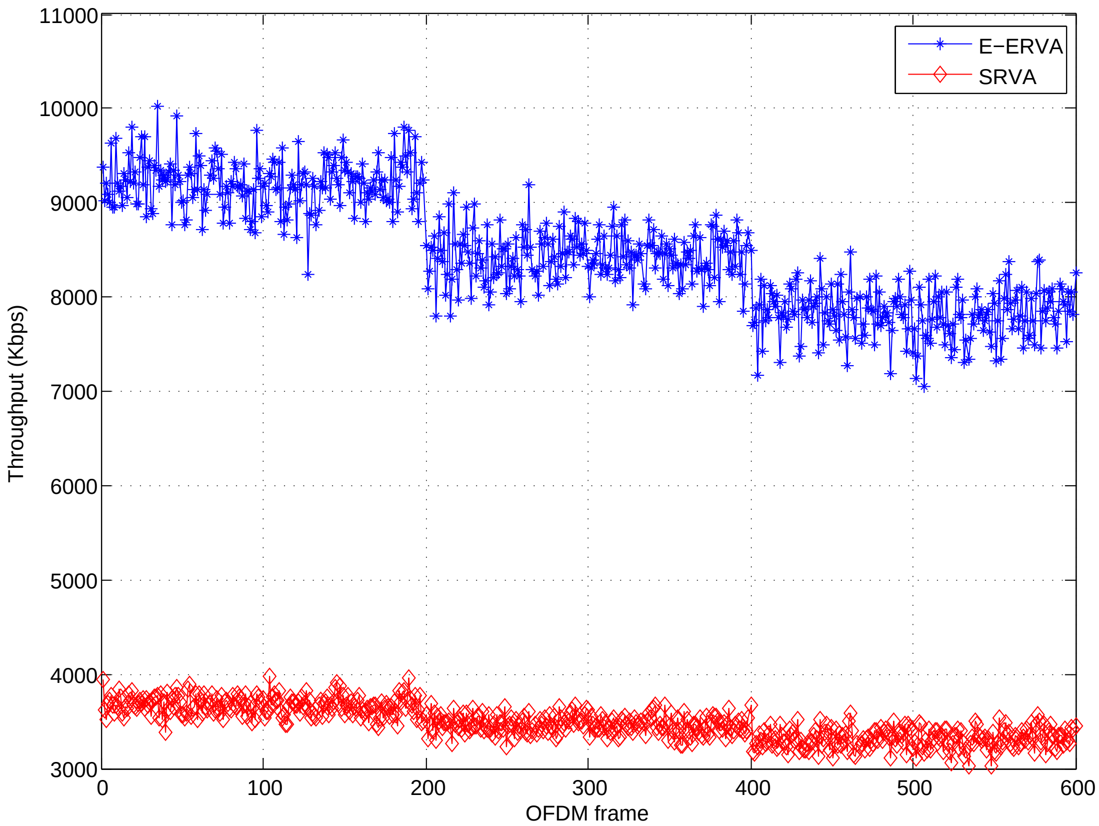

FIGURE 3.3: Throughput with different BER

FIGURE 3.4 illustrates the simulation of delivery ratio under different traffic loads. The delivery ratio is defined as $Data_D/Data_R$ where $Data_D$ is the successful delivered data rate and $Data_R$ is the total amount of requested data rate. When the requests are light, both E-ERVA and SRVA satisfy the foreign and local requests. However, with the traffic load increasing, the delivery ratio decreases in both algorithms where SRVA droops more dramatically. When the requests are over the total available resources, the delivery ratio of E-ERVA and SRVA are the same.

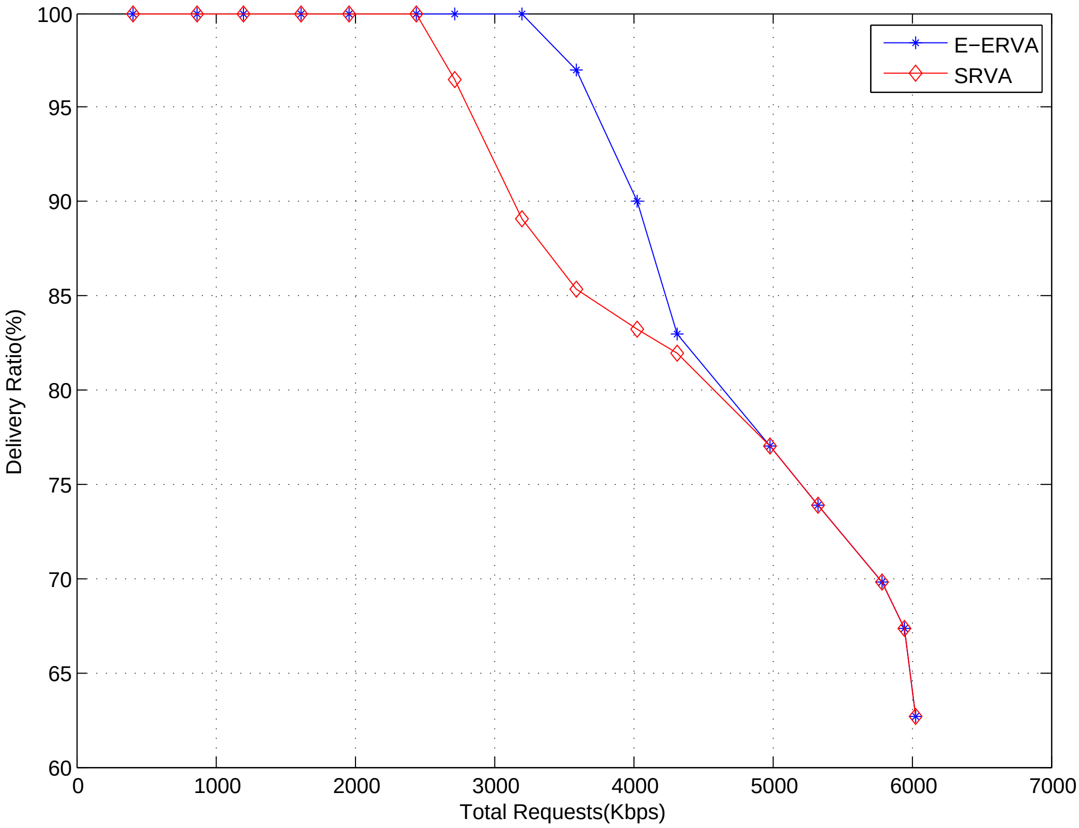

FIGURE 3.4: Delivery Ratio

The following figure displays resource utilization of E-ERVA and SRVA. The resource utilization is defined as $Data_{allocated}/Data_{total}$. In FIGURE 3.5, it can be seen that the resource utilization varies according to the traffic load. When the requests are small, both E-ERVA and SRVA can satisfy the requests. Thus the resource utilization is the same. However, with the demands increasing, as E-ERVA allows foreign or local slices use the spare resources, the requests can be satisfied under E-ERVA. In SRVA, on the other hand, foreign slices cannot use those resources even though there are spare resources after satisfying the local slice. Similarly, the local slice would not allow to assign the remainder resources if the local slice's requests exceed the upper limit. Hence, the resource utilization of E-ERVA is higher than SRVA due to the flexibility of E-ERVA. Nevertheless, as the requests keep increasing, the performance of E-ERVA and SRVA are the same due to the requests from all slices exceed the total amount of resources. Hence the resources are fully assigned to foreign and local slices.

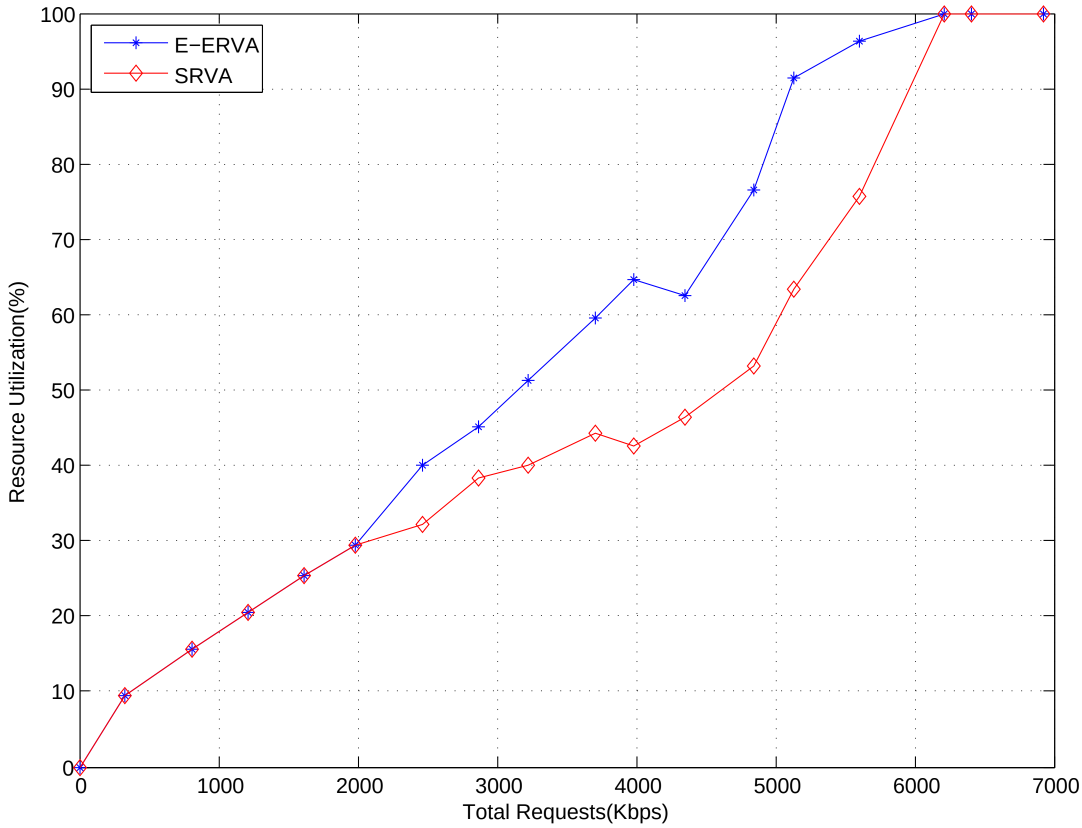

FIGURE 3.5: Resource Utilization

The following simulation evaluates four groups of requests from foreign and local slices. Two foreign slices (S1,S2) and one local slice (S0) are estimated. FIGURE 3.6 - 3.9 display the simulation results where E represents E-ERVA and S is SRVA. FIGURE 3.6 shows the result when foreign requests are less than SLA and local requests are less than the Upp. In FIGURE 3.7, the requests from foreign slices are less than the SLA, therefore there are spare resources after satisfying foreign slices. On the other hand, the requests from local slices are over the Upp while the excess requests is bounded by applying SRVA. However, E-ERVA allows the local slice using the spare resources. Thus the demand of S0 can be satisfied. Similarly in FIGURE 3.8, with E-ERVA both foreign slices can be satisfied by using the remainder resources whereas in SRVA the excess requests have to be bounded. In short, E-ERVA provides more flexibility to resources allocation. This results in a higher resources utilization. Finally in FIGURE 3.9, the total requests are more than the available resources, therefore the extra requests are bounded in E-ERVA as well as SRVA.

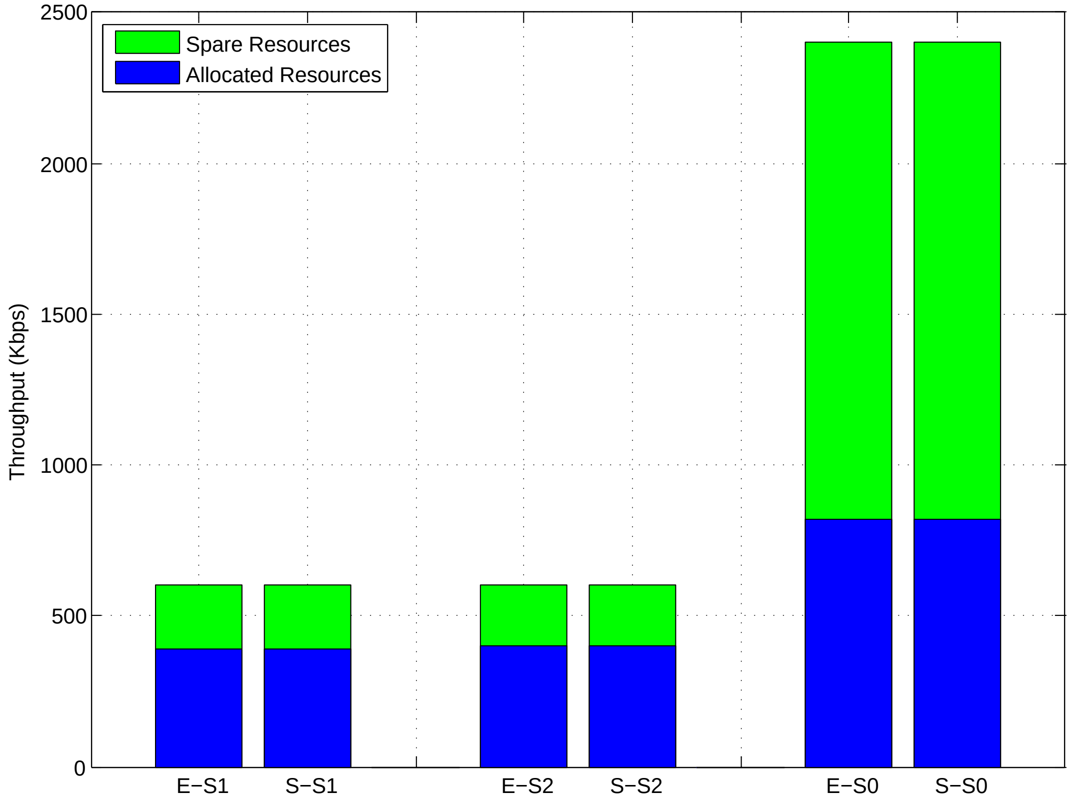

FIGURE 3.6: Foreign ≤ SLA, Local ≤ UPP

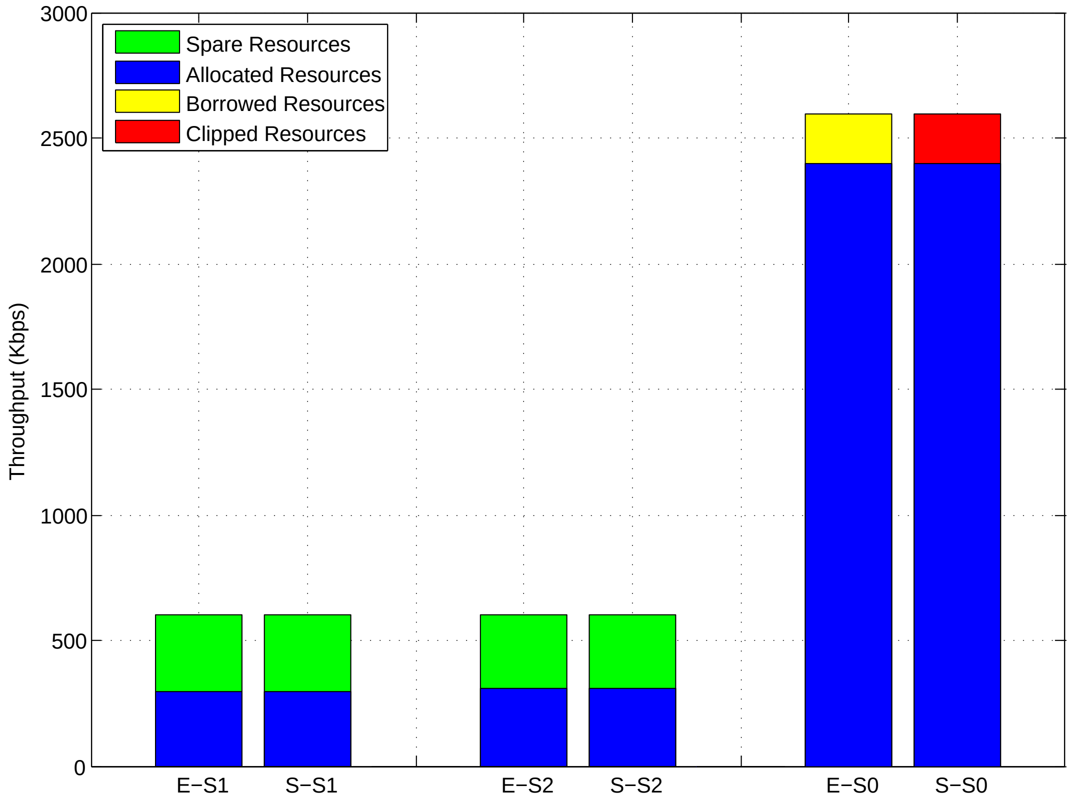

FIGURE 3.7: Foreign ≤ SLA, Local ≥ UPP

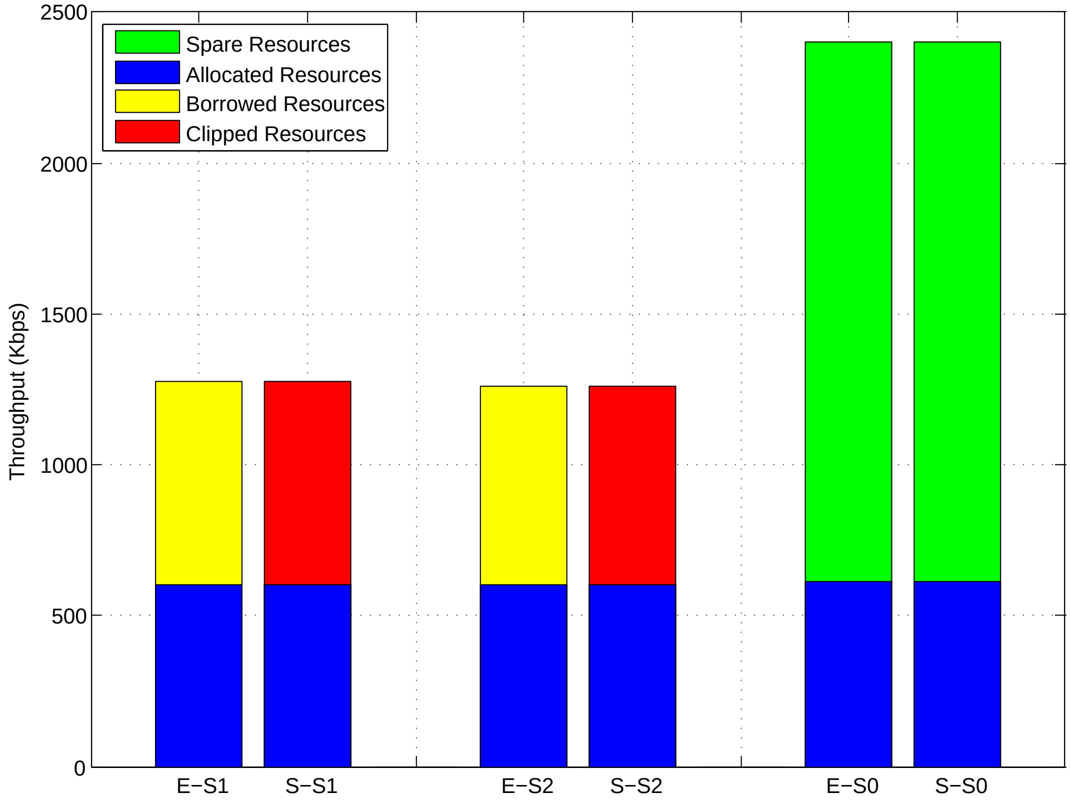

FIGURE 3.8: Foreign ≥ SLA, Local ≤ UPP

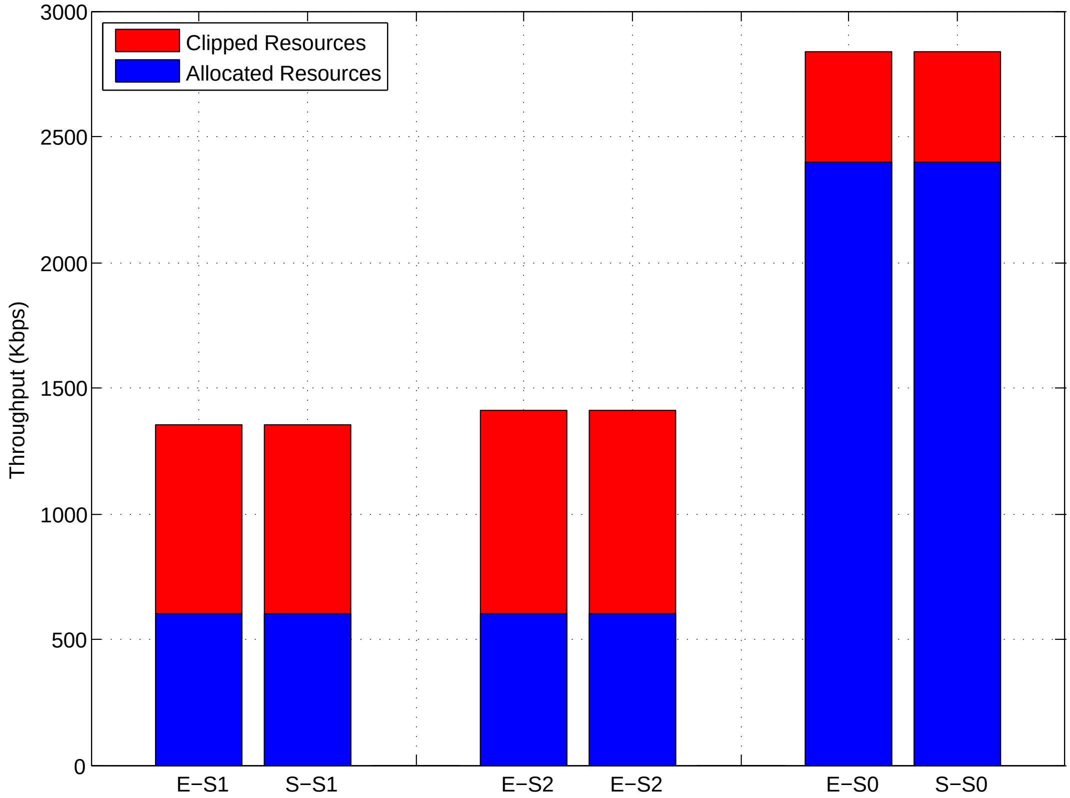

FIGURE 3.9: Foreign ≥ SLA, Local ≥ UPP

The final simulation compares three algorihms: E-ERVA, ERVA and SRVA. E-ERVA and SRVA have a total bandwidth of 1.4MHz and ERVA has a total bandwidth of 2MHz. In addition, Three algorithm have the SNR of 15dB. It can be observed from FIGURE 3.10 that E-ERVA ahieves the highest throughput. E-ERVA is an enhanced algorithm of ERVA. Because E-ERVA allows both local and foreign slices use the spare resources, it is more elastic than ERVA. ERVA does not allow foreign slices use spare resources even the local slice satisfies its own end users. On the other hand, the local slice is allowed to use the remaining resources if foreign slices satisfy users. Thus, E-ERVA performs better than ERVA. In SRVA, foreign slices are assined the fix amount of resources regardless of both local and foreign slices' users, thus it has the lowest throughput.

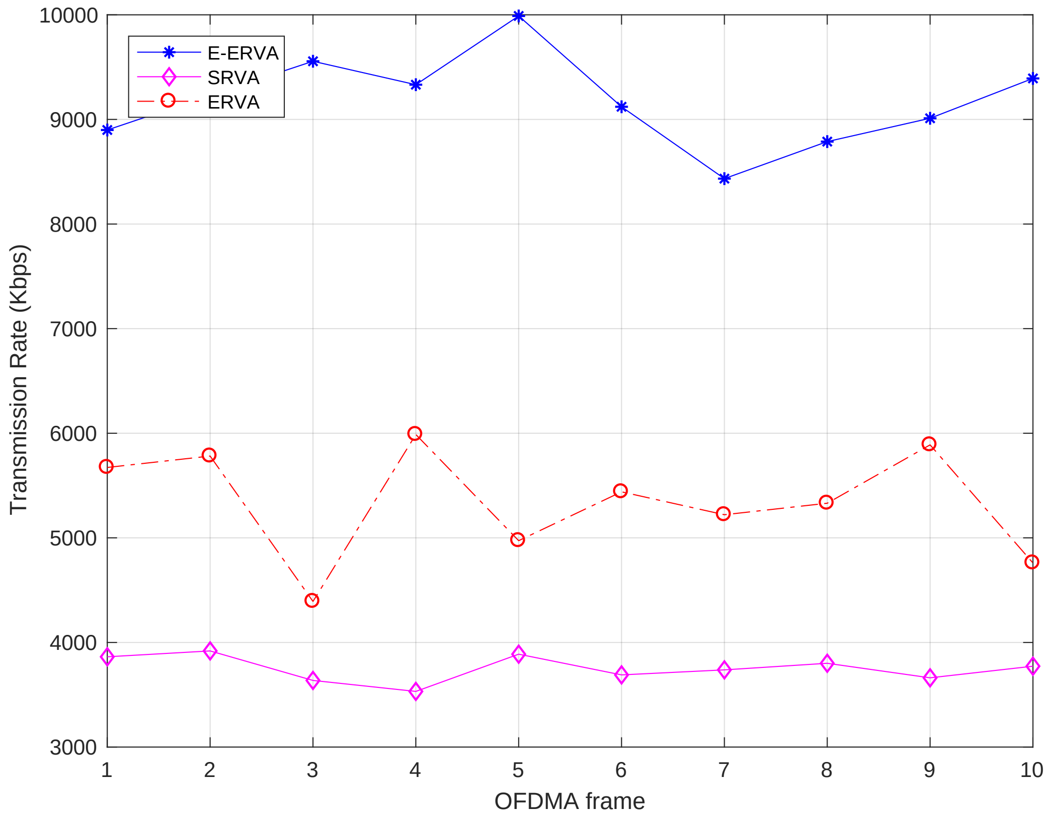

FIGURE 3.10: Camparison of three algorithms

3.4 Summary

The evaluation results show the benefits of applying E-ERVA. Compared to SRVA, E-ERVA possesses a higher throughput. This is because E-ERVA allows either foreign or local slices to use the spare resources. By the means of this algorithm, the resource utilization can be improved. Moreover, the delivery ratio is higher than SRVA.

E-ERVA is an evolved algorithm of ref. [65]. The main difference between them is E-ERVA allows foreign and local slices use spare resources while ERVA only allows local slice to use it. Thus, a higher resources utilization can be achieved comparing to ERVA. This can be found from FIGURE 3.10. In short, E-ERVA provides more flexibility to both foreign and local slices.

Chapter 4

Power Allocation Algorithm

Within the WNV environment, if resources (e.g. power or spectrum) are not fully used, the InP has an interest to sell them to VNOs. This is referred to as the resources trading mechanism which involves resources selling and buying processes. Therefore, it provides the opportunity for applying a *buyer-seller model* in resources sharing. Alternative approaches to the research of the resource sharing problem in wireless communication based on an economic model have been presented in [108, 109]. Following this model, a utility function is introduced as a measurement of each player's level of satisfaction achieved from using the system resources [110]. A game theory based solution to the resource sharing problem is presented in this section. Game theory is commonly used in microeconomics while it is an efficient tool in modelling interactions between self-interest players and predicting their preference of strategies [111], [112]. Each player in the game intends to maximizes some functions of utility in a distributed manner. Due to the players acting selfishly, the equilibrium point is not the best operating point. Pricing-based resource allocation algorithm is generally adopted in cognitive radio networks (CRNs) [113–115]. However, some research work in WNV resource allocation that based on the consideration of price. The work of this section considers a WNV transmission system where several VNOs can improve their utilities by sharing the spare power from an InP. The VNO's strategy selection is formulated as a non-cooperative game which bases on the price information that is provided by the InP. Taking this price information into account, the InP adjusts the amount of allocated power to VNOs, while the adjust speed is controlled by a learning rate. Since each VNO aims to maximize its own utility, there exists an equilibrium point which enables no VNO can improve its utility by adopting a different strategy. To sum up, the purpose of the power allocation game is to find out the equilibrium point that can maximize each VNO's utility via the InP's power allocation. Therefore, this section proposes a pricing-based power allocation algorithm for a QoS aware WNV transmission system. This work has been peer reviewed and published on *2015 International Wireless Communications and Mobile Computing Conference* [127].

4.1 System Model

According to the previous charpter, the InP generates a VN to serve its own users where this VN is called local slice and denoted by S_0. On the other side, VNs that serve VNOs' users are named foreign slices which are represented by S_i, $(i = 1, \ldots, n)$. The algorithm considers a downlink OFDMA-based WNV with one local slice and n foreign slices. The utility of a foreign slice is measured in bits per joule energy by a utility function. The concept of utility function is commonly used in microeconomics and refers to the satisfaction level that the decision maker receives due to its actions [110]. In this algorithm, the utility function indicates how many bits can be successfully received by the foreign slice per joule energy. A power allocation algorithm is applied in order to achieve the maximum individual foreign slice's utility with the consideration of a price function which is defined by the local slice. FIGURE 4.1 shows the system model for power allocation of WNV. The local slice has a spare power amount of P and expects to share it with foreign slices. The InP determines the size of assigned power p_i to S_i according to its utility.

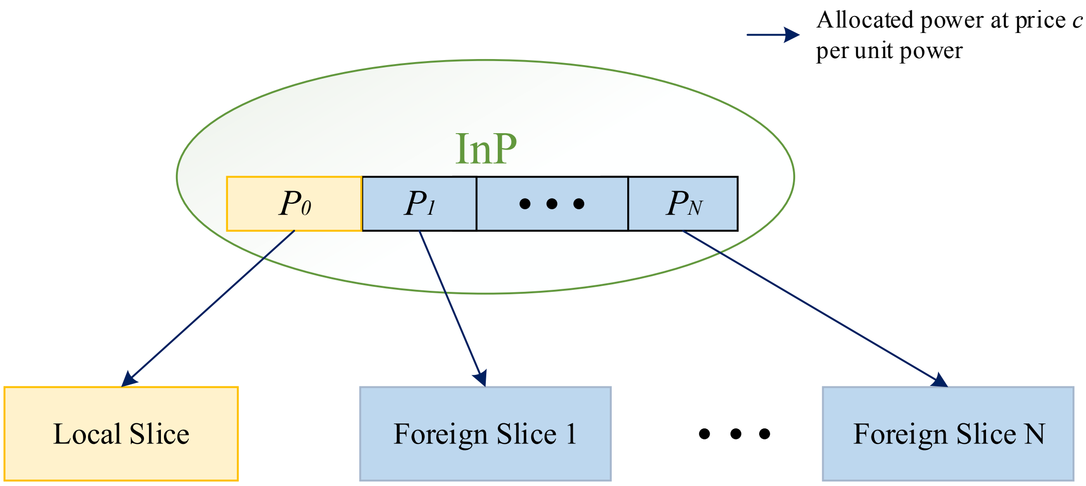

Figure 4.1: System model of WNV power allocation

4.2 Proposed Power Allocation Algorithm

Assume that each foreign slice is assigned the same amount of physical resource blocks (PRBs). In a multi-slice transmission system, consider the InP transmits L bits payload in frames of M bits where $M > L$, let β_f denotes the probability of correct reception of a frame at the receiver. According to [110], the utility function of S_i can be expressed as

$$U_i = \frac{Lr\beta_f}{Mp_i} \quad \text{bits/joule} \tag{4.1}$$

where r is the transmission rate, and p_i presents the allocated powe to slice i. Eq. (4.1) is the utility function of S_i which describes how many bits can be successfully be received by S_i per joule energy.

Assuming perfect error detection and no error correction, β_f can be expressed as $\beta_f = (1 - \beta_e)^M$ where β_e is the bit error rate (BER). In all conditions, β_e decreases monotonically with the signal-to-interference-noise ratio (SINR) which is denoted by γ. Therefore, β_f is a monotonically increasing function of γ. The SINR is defined as

$$\gamma_i = \frac{p_i g_i}{\sum_{i \neq j} p_j g_j + \sigma^2} \tag{4.2}$$

where p represents the transmission power, g is the power channel gain and σ^2 is the Gauss-distributed standard deviation of the noise. BER has different expressions with different modulation schemes. Consider differential phase-shift keying (DPSK) as the modulation scheme, β_e can be express as a function of SINR: $\beta_e = \frac{1}{2}e^{-\gamma}$ which results in $\beta_f = (1 - \frac{1}{2}e^{-\gamma})$.

However, for all modulation schemes $p = 0$ leads to $\gamma = 0$, which causes $\beta_f = \frac{1}{2}$. It is the worst case for β_f. In other words, the best strategy for the receiver is to make a guess to every received bit. Thus, it would lead to an infinite utility. In order to avoid this mathematical limitation, β_f can be approximated by an efficiency function that closely follows the behaviour of the probability of correct reception. Consequently, the efficiency function is defined as

$$\beta_f = (1 - 2\beta_e)^M \tag{4.3}$$

Regarding to Eq. (4.2), the efficiency function can be rewritten as

$$f(\gamma) = (1 - e^{-\gamma})^M \tag{4.4}$$

where $f(\gamma)$ describes the probability of frame correct reception. Therefore, the utility function can be rewritten as

$$\begin{aligned} U_i &= \frac{Lrf(\gamma_i)}{Mp_i} \\ &= \frac{Lr(1 - e^{-\frac{p_i g_i}{\sum_{i \neq j} p_j g_j + \sigma^2}})}{Mp_i} \quad \text{bits/joule} \end{aligned} \tag{4.5}$$

The efficiency function corresponds the desirable feature $f(0) = 0$ for $p = 0$ and $f(\infty) = 1$. Let γ_0 denotes the SINR of the local slice, there is

$$\gamma_0 = \frac{p_0 g_0}{\sum_{i \in \{1,\ldots,n\}} p_i g_i + \sigma^2} \tag{4.6}$$

where p_0 and g_0 are the transmission power and channel gain of the local slice respectively. The minimum SINR requirement of S_0 is denoted by $\widetilde{\gamma}$. Thus the condition $\gamma_0 \geq \widetilde{\gamma}$ is necessary to ensure that S_0 is willing to share power with foreign slices which results in $\sum_{i \in \{1,\ldots,n\}} p_i g_i \leq (p_0 g_0 - \widetilde{\gamma}\sigma^2)/\widetilde{\gamma}$.

The local slice charges a foreign slice of c per unit allocated power where c is a function of the total amount of the power available for allocating. The pricing function is given by [128] as follows

$$c(P) = a + b\left(\sum_{p_j \in P} p_j\right)^{\tau} \tag{4.7}$$

where a, b and τ are non-negative constants. In particular, $\tau \geq 1$ ensures the convexity of the pricing function. P denotes the set of strategies of all foreign slices (i.e. $P = \{p_1, p_2, ..., p_N\}$). The pricing function has the units $bit/second/Watt^2$ which is consistent with the units of the utility. Note that the local slice charges all foreign slices at the same price.

Based on the above description, a non-cooperative game can be formulated as follows. Players in this game are foreign slices and the strategies of slice i is the allocated power p_i which is non-negative. The revenue of S_i can be obtained from U_i where the cost of allocated power is $p_i \times c(P)$. The payoff function of S_i can be written as:

$$\Phi_i(P) = \frac{Lrf(\gamma_i)}{Mp_i} - p_i\left[a + b\left(\sum_{p_j \in P} p_j\right)^{\tau}\right] \tag{4.8}$$

Each individual foreign slice competes for the available power to maximize its own utility, therefore the energy efficient power allocation problem can be formulated as follows:

$$\max_{p_i} \ \Phi_i = \frac{Lrf(\gamma_i)}{Mp_i} - p_i \left[a + b \left(\sum_{p_j \in P} p_j \right)^{\tau} \right] \forall i \in \{1, 2, \ldots, n\} \tag{4.9}$$

The solution of this non-cooperative game is widely used in game theory which is known as Nash equilibrium. Consider a n foreign slices WNV transmission system and N denoted the set of foreign slices, it has

Definition 4.1. A Nash equilibrium is a strategy space $\boldsymbol{p}^* \in P$ that $\forall i \in N$, it has

$$\Phi_i(p_i^*, \boldsymbol{p}_{-i}^*) \geq \Phi_i(p_i, \boldsymbol{p}_{-i}^*), \ \forall i \in N \tag{4.10}$$

where $\boldsymbol{p}_{-i}$ denote the set of strategies adopted by all foreign slices except S_i, i.e. $\boldsymbol{p}_{-i} = \left\{ p_j \mid j = 1, 2, ..., n; j \neq i \right\}$ and $P = \{\boldsymbol{p}_{-i}\} \cup \{\boldsymbol{p}_i\}$. In other words, a strategy space is a Nash equilibrium if no player has a trend attempting to adopt another strategy, given that other players' strategies remain fixed.

4.2.1 Solution of the power allocation game

Definition 4.2. The best response function $BR_i(\boldsymbol{p}_{-i})$ of a player i to the strategy space $\boldsymbol{s}_{-i}$ is a set of strategies for the player that

$$BR_i(\boldsymbol{p}_{-i}) = \{p_i \in \boldsymbol{P}_i \mid \Phi_i(p_i, \boldsymbol{p}_{-i}) \geq \Phi_i(p_i', \boldsymbol{p}_{-i}), \ \forall p_i' \in \boldsymbol{P}_i\} \tag{4.11}$$

The best response function describes that if each of the other player j follows $\boldsymbol{p}_{-i}$ then player i cannot improve its performance than to choose a value of $BR_i(\boldsymbol{p}_{-i})$.

Proposition 4.3. *A strategy space $\boldsymbol{p}^* \in P$ is a Nash equilibrium of a non-cooperative game if and only if every slice's strategy is a best response to the other slices' strategies, that is*

$$\boldsymbol{p}_i^* \in BR_i(\boldsymbol{p}_{-i}^*) \quad \forall i \in N \tag{4.12}$$

Eq. (4.9) is a non-cooperative game. In order to solve this game, the marginal profit function for S_i is introduced from

$$\frac{\partial \Phi_i(P)}{\partial p_i} = \frac{Lrf'(\gamma_i)}{Mp_i} - \frac{Lrf(\gamma_i)}{Mp_i^2} - a - b\left(\sum_{p_j \in P} p_j\right)^{\tau} - bp_i\tau\left(\sum_{p_j \in P} p_j\right)^{\tau-1} \tag{4.13}$$

The optimal size of allocated power to one foreign slice depends on the actions that are taken by other foreign slices. As mentioned before, to make sure all foreign slices are satisfied, Nash equilibrium (NE) is considered as the solution of this game.

By definition, NE is a strategy profile with the property that no player can increase its payoff by choosing a different strategy. In this case, the NE is obtained by using the best response function which indicates the best strategy of one player given others' strategies. The best response function of S_i gives the size of allocated power p_i by other foreign slices' p_j where $j \neq i$ and is defined as follows:

$$BR_i(P_{-i}) = \arg\max_{p_i} \Phi_i(\{p_{-i}\} \cup \{p_i\}) \tag{4.14}$$

The set $P^* = \left\{p_1^*, p_2^*, ..., p_N^*\right\}$ denotes the NE of the game if and only if

$$p_i^* = BR_i(P_{-i}^*), \quad \forall i \in N \tag{4.15}$$

where $\left\{P_{-i}^*\right\}$ represents the set of best responses for S_j ($j \in N, j \neq i$). Consequently, the following equation is needed to be solved in order to achieve NE.

$$\frac{\partial \Phi_i(P)}{\partial p_i} = \frac{Lrf'(\gamma_i)}{Mp_i} - \frac{Lrf(\gamma_i)}{Mp_i^2} - a - b\left(\sum_{p_j \in P} p_j\right)^{\tau} - bp_i\tau\left(\sum_{b_j \in P} p_j\right)^{\tau-1} = 0 \tag{4.16}$$

In WNV environment, foreign slice only can obtain the price information from the local slice. One foreign slice cannot observe other foreign slices' strategies and profits which results a noncooperative game. Thus the NE for each foreign slice is obtained based on the interaction with the local slice only. Since all foreign slices aim to maximize their own profits, they adjust the size of the requested power p_i based on the marginal profit function. The adjustment of the allocated power can be modelled as a power allocation game as following:

$$p_i(t+1) = p_i(t) + \theta p_i(t) \frac{\partial \Phi_i(P)}{\partial p_i(t)} \tag{4.17}$$

where $p_i(t)$ is the allocated power size at time t and θ is the adjustment speed parameter of S_i. The adjustment speed means how past p_i converges to the optimum value.

In an actual transmission system, the value of $\frac{\partial \Phi_i(P)}{\partial p_i(t)}$ can be estimated by foreign slices. To be more specific, a foreign slice inquires the local slice of the price c at time t by submitting the power size $p_i(t) \pm \varepsilon$, where ε is a small number. Thus the foreign slice observes the response price $c^-(\cdot)$ and $c^+(\cdot)$ for $p_i(t) - \varepsilon$ and $p_i(t) + \varepsilon$ respectively [128]. With these information, $\Phi_i^-(\cdot)$ and $\Phi_i^+(\cdot)$ can be calculated and the margin profit can be estimated from

$$\frac{\partial \Phi_i(P)}{\partial p_i} \approx \frac{\Phi_i^+(t) - \Phi_i^-(t)}{2\varepsilon} \tag{4.18}$$

Therefore, a noncooperative power allocation algorithm for foreign slices can be proposed in the following.

Algorithm 2 Noncooperative Power Allocation Game

Input: $L,\ M,\ r,\ g_i,\ \beta_e,\ \widetilde{\gamma},\ \varepsilon,\ \theta$

1: **for** each foreign slice i, $i \in N$ **do**
2: Initialize p_i
3: **if** $\sum_{i \in N} p_i g_i \leq (p_0 g_0 - \widetilde{\gamma}\sigma^2)/\widetilde{\gamma}$ **then**
4: $\Phi_i^+(t) = \frac{Lr(1-2\beta_e)^M}{M(p_i+\varepsilon)}$ and $\Phi_i^-(t) = \frac{Lr(1-2\beta_e)^M}{M(p_i-\varepsilon)}$
5: $\frac{\partial \Phi_i(P)}{\partial p_i} \approx \frac{\Phi_i^+(t) - \Phi_i^-(t)}{2\varepsilon}$
6: **Update** p_i by
7: $p_i(t+1) = p_i(t) + \theta p_i(t) \frac{\Phi_i^+(t) - \Phi_i^-(t)}{2\varepsilon}$
8: **if** $p_i(t+1) \neq p_i(t)$ **then**
9: Go to 3
10: **else**
11: The NE is $P^* = \{p_1, p_2, ..., p_i\}$
12: **end if**
13: **end if**
14: **Return** best strategy P^*
15: **end for**

Noticed that the local slice is willing to share the spare power with foreign slices only when the local slice satisfies their own users. In this algorithm, the local slice satisfies the users' SINR requirements. This constrains is judged in line 3. If the local slice is able to share spare power with foreign slices, the margin profit $\frac{\partial \Phi_i(P)}{\partial p_i}$ is calculated then the allocated power is achived by line 7. Line 8 is the condition of wether p_i is converged. If p_i does not reach the optimum value, $p_i(t)$ is updated to $p_i(t+1)$ and the process returns to line 3 until the best strategy P^* is found.

This algorithm focuses on the downlink power allocation in OFDMA WNV consisting of multiple foreign slices. To maximize each individual slice's utility (i.e. maximize the amount of bits can be successfully received per joule energy), a noncooperative game with NE is introduced as its solution. At an NE, no foreign slice can increase its utility by changing individual power selection with the given power of other foreign slices.

4.2.2 Inefficiency of Nash equilibrium

In order to obtain the Nash equilibrium, it requires to solve n maximization problems, namely

$$\max_{p_1} \Phi_1(p_1), \max_{p_2} \Phi_2(p_2), \ldots, \text{and } \max_{p_n} \Phi_n(p_n) \tag{4.19}$$

The solution is to take the first order derivation for each slice i, $\forall i \in N$.

$$\frac{\partial \Phi_1(p_1)}{\partial p_1} = 0, \frac{\partial \Phi_2(p_2)}{\partial p_2} = 0, \ldots, \text{ and } \frac{\partial \Phi_n(p_n)}{\partial p_n} = 0 \tag{4.20}$$

Consider the overall utility as

$$\max_{p_i} \sum_{i=1}^{n} \Phi_i(p_i) \tag{4.21}$$

then the solution is

$$\begin{aligned}
&\frac{\partial \Phi_1(p_1)}{\partial p_1} + \frac{\partial \Phi_2(p_2)}{\partial p_1} + \cdots + \frac{\partial \Phi_n(p_n)}{\partial p_1} = 0,\\
&\frac{\partial \Phi_1(p_1)}{\partial p_2} + \frac{\partial \Phi_2(p_2)}{\partial p_2} + \cdots + \frac{\partial \Phi_n(p_n)}{\partial p_2} = 0,\\
&\qquad\qquad\vdots\\
\text{and } &\frac{\partial \Phi_1(p_1)}{\partial p_n} + \frac{\partial \Phi_2(p_2)}{\partial p_n} + \cdots + \frac{\partial \Phi_n(p_n)}{\partial p_n} = 0
\end{aligned}$$

Compare the solutions of Eq. (4.19) and (4.21), it can be observed that the maximum overall utility takes $\frac{\partial \Phi_2}{\partial p_1}, \frac{\partial \Phi_1}{\partial p_2} \ldots \frac{\partial \Phi_i}{\partial p_j}$ $(i, j \in N, i \neq j)$ into account. Namely the actions of S_i may harm the interests of S_j's and vice versa. These are ignored in the Nash equilibrium as the Nash equilibrium is only optimal when $\frac{\partial \Phi_2}{\partial p_1} = \frac{\partial \Phi_1}{\partial p_2} = \cdots = \frac{\partial \Phi_i}{\partial p_j} =$

TABLE 4.1: The list of parameter setting for the OFDMA WNV power allocation algorithm evaluation

L	Number of payload bits per frame	64
M	Total number of bits per frame	80
R	Transmission rate	64 kbps
σ^2	AWGN power	10^{-13} watts
ε	Adjustment size	10^{-6}
θ	Step size	10^{-6}
$\widetilde{\gamma}$	Requirement SINR of the local slice	12dB
a		0
b	Price function parameter	0.5
τ		1

0 $(i, j \in N, i \neq j)$. To sum up, the Nash equilibrium optimize the individual slice's utility rather than the overall utility.

4.3 Simulation Results and analysis

To evaluate the performances of the proposed algorithm, Table 4.1 shows the simulation parameter setting. The evaluation is based on a one local slice with two foreign slices case. However, the model can be used in a multi local to multi foreign slices manner. Besides, g represents the channel gain.

The parameter is based on a voice over LTE tranmission frame. The transmission rate is the lowest gauranteed transfer speed. To simplify the calculation process, parameters of pricing funtion are set small. In addition, the simulation also observes how the converged speed is affect by the pricing function parameters.

The best response (BR) functions of Slice 1 (BR_1) and Slice 2 (BR_2) are shown in FIGURE 4.2. The Nash equilibrium (NE) is located at the point where the best responses of both foreign slices intersect. According to Eq. (4.14), p_i^* depends on $\left\{P_{-i}^*\right\}$. In other words, the allocated power of Slice 1 p_1 varies according to the allocated power of Slice 2 p_2. If slice 1 chooses another strategy, the amount of allocated power of slices will be changed. The intersection point of the two slices fulfils the Eq. (4.14). The NE point means that slice 1 and slice 2 cannot improve their utilities by adopting another power value. In addition, the total allocated power can be calculated by NE.

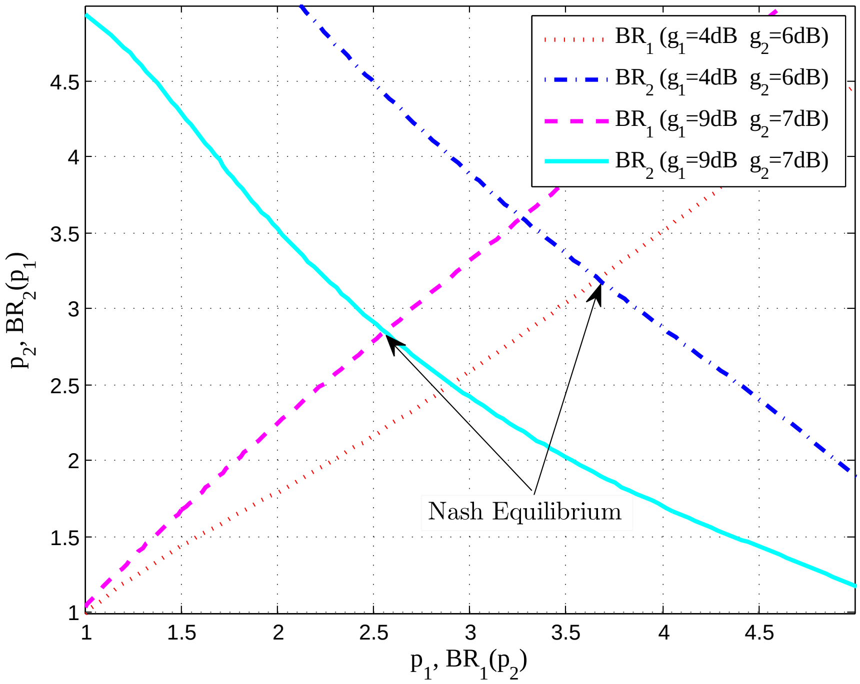

FIGURE 4.2: Best response function and Nash equilibrium

FIGURE 4.3 displays the total utilities of both foreign Slice 1 and Slice 2. Due to the channel gain differences (i.e. $g_1 = 4dB, g_2 = 6dB$ and $g_1 = 9dB, g_2 = 7dB$) the total utility varies. It is clear that better channel quality results in a higher utility while with less power allocated. In addition, it is also known from the figure that the overall utility is not maximized with the NE due to each foreign slice acts selfishly. Because it is a non-cooperative game, each slice does not know the information of another slice while each slice is only trying to maximize its own utility. Hence the foreign slices request power as much as possible. This also indicates the inefficiency of the NE.

In FIGURE 4.4, the pricing function refers to Eq. (4.7) which means the local slice charging foreign slices at c per unit allocated power. The channel gain is set as $g_2 > g_1$,

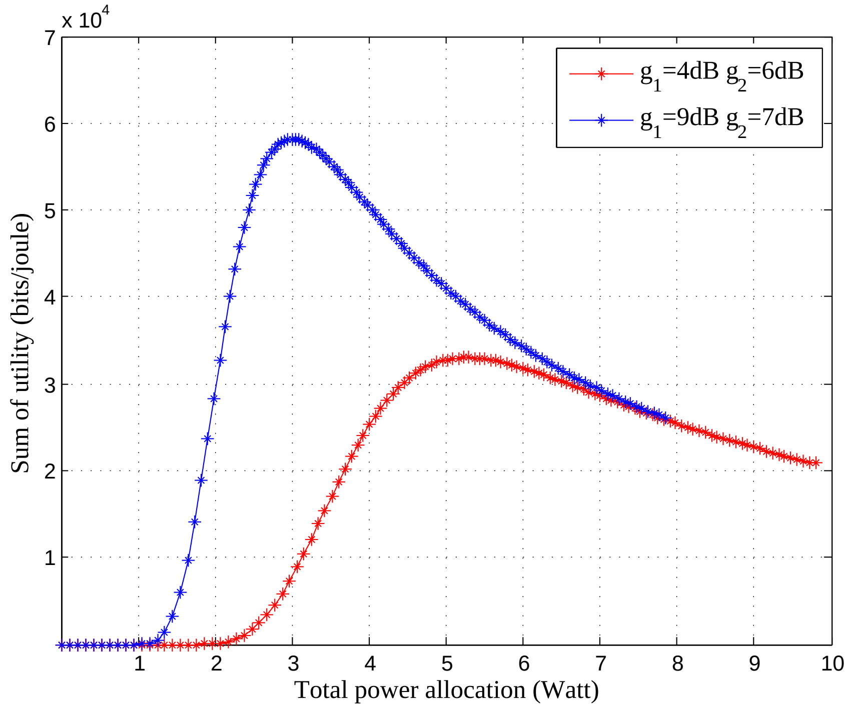

FIGURE 4.3: Utility as a function of the transmit power

thus Slice 2 achieves maximum utility at lower price compare to Slice 1. Similar to the utility function, the pricing function is also strictly concave. This is because the utility function represents the satisfaction of each user. In another word, the local slice will

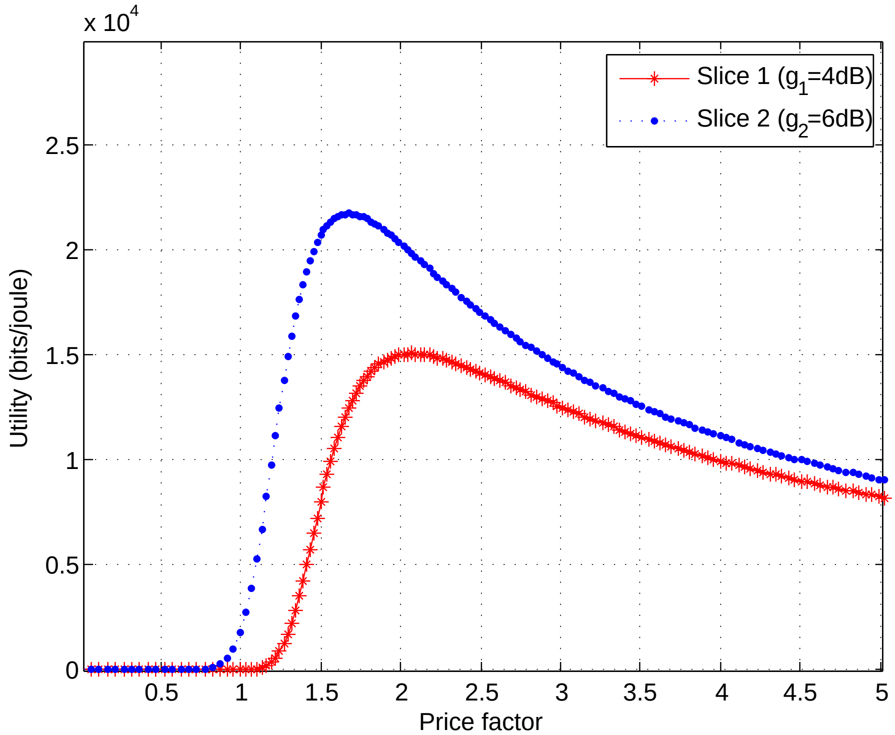

FIGURE 4.4: Pricing function c vs. utility

increase its resource price if there is purchase from foreign slices. However, there is a upper bound of the price that foreign slices can accept. Once the price over this bound, foreign slices will not purchase because there is no profit to be obtained. Hence the price drops after the upper bound. This is how the price relates to the utility.

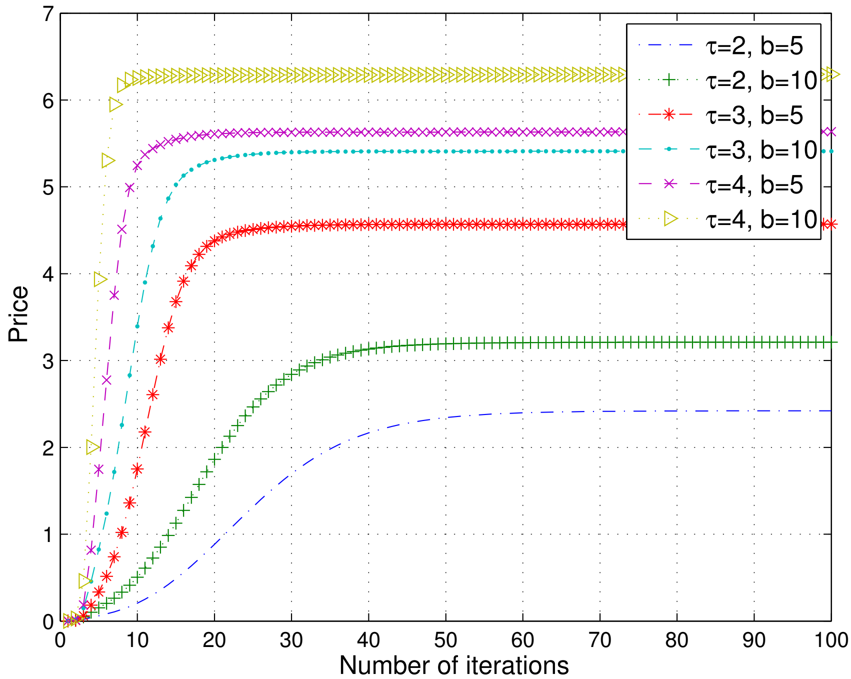

FIGURE 4.5: Pricing function parameters effect

FIGURE 4.5 displays how the parameters b and τ affect the pricing function. It is clearly that the price converges faster with larger b and τ. In particular, τ has more effect to the pricing function and $\tau \geq 1$ is the constraint that ensures Eq. (4.7) is convex. The parameters b and τ in the pricing function $c(P)$ affect the best response function and the NE. With a larger b or τ, the local slice charges more for the same amount of shared power. Thus, the profits of foreign slices decrease such that they show less interest for buying power and the amount of the allocated power of each foreign slice becomes smaller.

4.4 Summary

In this section, a power allocation algorithm for downlink OFDMA WMV based on a pricing function is proposed. A dynamic non-cooperative game is employed which considers the benefits of foreign slices. The algorithm helps each foreign slice maximizing their own utilities. By means of power allocation, the NE as the best strategy for foreign slices has been found. Due to each foreign slice acts selfish, it only considers its own utility rather than the overall utility. Although the NE for this power allocation algorithm is inefficient for which the total utility of all foreign slices is not maximized, it still provides a fair solution to power sharing.

Chapter 5

Joint Power and Subchannel Allocation Algorithm

This chapter proposes a multiple iterations algorithm across power and subchannel allocation on an WNV basis. To the best of the authors' acknowledge, only a few works have studied virtual resources allocation. In addition, the majority of the joint power and subchannel allocation algorithms only consider one-off allocation. This means after first gaining a subchannel allocation value, the power allocation is obtained accordingly. However, once the power level changes, the number of allocated subchannels should be modified as well. Therefore, it is more reasonable to introduce multiple iterations. This work has been submitted to *Springer Journal of Wireless Personal Communication* on June 2016.

5.1 System Model

Regarding to the definition of WNV, InPs also generate VNs to serve their own users where these VNs are called local slices. In addition, the VNs which are created by VNOs are named foreign slices. Let $\mathcal{L}$ denotes the set for local slices and $\mathcal{F}$ the set for foreign slices. The total slices set is $\mathcal{I} = \mathcal{L} \cup \mathcal{F}$. The joint power and subchannel allocation algorithm considers a downlink OFDMA-based WNV communication environment with the total B Hz channel bandwidth is divided into M orthogonal subchannels and the bandwidth size of each subchannel is b_0. In addition, it is assumed that a foreign slice will spread the available power evenly on the assigned subchannel and the noise power density is $N_0/2$. Let S_i represents the i-th slice, then the data rate of S_i is [126] [126]

$$r_i = \sum_k n_i^k b_0 \log_2(1 + \frac{g_i^k p_i^k}{n_i^k b_0 N_0}) \tag{5.1}$$

where n_i^k is the number of allocated subchannel from k-th InP to i-th slice. p_i^k denotes the transmission power from k-th InP to i-th slice where g_i^k is the channel power gain from k-th InP to S_i. FIGURE 5.1 shows an illustrative sample of WNV architecture. Notice that k-th InP is allowed to share resources with more than one foreign slice while i-th slice can borrow resources from more than one InP. In order to obtain the maximum data rate, the first step is to apply the subchannel allocation scheme with fix power level which is proposed below.

Moreover, eq. (5.1) is strictly concave in $(\boldsymbol{n}, \boldsymbol{p})$. The concavity is essential for optimization problem. Namely there is an optimum value exists if the function is concave. The proof is shown below.

To show the concavity of Eq. (5.1), turn the formulation into the following general form.

$$f(n, p) = n \log_2 \left(1 + \frac{p}{n}\right) \tag{5.2}$$

The first partial derivatives of $f(n, p)$ are

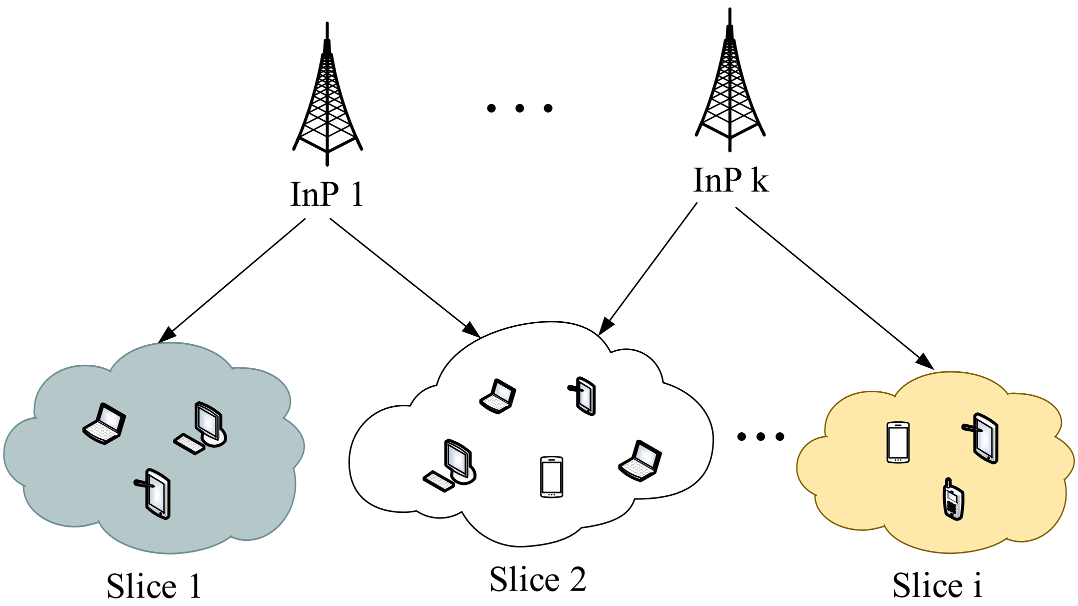

FIGURE 5.1: A sample of WNV transmission environment

$$\frac{\partial f}{\partial n} = \log_2\left(1 + \frac{p}{n}\right) - \frac{p}{\ln 2(n+p)} \tag{5.3}$$

$$\frac{\partial f}{\partial p} = \frac{n}{\ln 2(n+p)} \tag{5.4}$$

Then the second order partial derivatives are

$$\frac{\partial^2 f}{\partial n^2} = -\frac{1}{n \ln 2}\left(\frac{p}{n+p}\right)^2 \tag{5.5}$$

$$\frac{\partial^2 f}{\partial n \partial p} = \frac{p}{\ln 2(n+p)^2} \tag{5.6}$$

$$\frac{\partial^2 f}{\partial p \partial n} = \frac{p}{\ln 2(n+p)^2} \tag{5.7}$$

$$\frac{\partial^2 f}{\partial p^2} = -\frac{1}{n \ln 2}\left(\frac{n}{n+p}\right)^2 \tag{5.8}$$

According to ref. [129], the Hessian matrix of function $f(n, p)$ is

$$H = \begin{bmatrix} -\frac{1}{n\ln 2}\left(\frac{p}{n+p}\right)^2 & \frac{p}{\ln 2(n+p)^2} \\ \\ \frac{p}{\ln 2(n+p)^2} & -\frac{1}{n\ln 2}\left(\frac{n}{n+p}\right)^2 \end{bmatrix} \tag{5.9}$$

Then the determinant of H is

$$\begin{aligned} \mid D \mid &= \left(\frac{1}{n\ln 2}\right)^2 \frac{p^2n^2}{(n+p)^4} - \frac{p^2}{(\ln 2)^2(n+p)^4} \\ &= \frac{p^2}{(\ln 2)^2(n+p)^4} - \frac{p^2}{(\ln 2)^2(n+p)^4} = 0 \end{aligned} \tag{5.10}$$

If the determinant is zero means the second derivative test of function $f(n, p)$ is inconclusive. Namely, $f(n, p)$ is convex if H is positive semi-define or $f(n, p)$ is concave if H is negative semi-define. Notice that the H is a symmetric matrix. The leading principal is

$$M = -\frac{1}{n\ln 2}\left(\frac{p}{n+p}\right)^2 \leq 0 \tag{5.11}$$

According to [130], function $f(n, p)$ is concave if the determinants have the following rules:

$$\mid D \mid \geq 0, \ \mid M \mid \leq 0 \tag{5.12}$$

It is observed from Eq. (5.10) and Eq. (5.11), $f(n, p)$ has the above pattern. Thus $f(n, p)$ is a concave function in $\{n, p\}$.

The objective function $f(n, p)$ contains two variables, therefore the general solution of identifying the concavity or convexity is not applied. In order to estimate this property of $f(n, p)$, Hessian matrix and the determinant are introduced.

5.2 Proposed Resource Allocation Algorithm

5.2.1 Subchannel Allocation Algorithm

In this subchannel allocation algorithm, each local and foreign slices are assigned the same amount of power. Under this condition, to obtain the amount of allocated subchannel of each slice. The MNV transmission maximization problem with InP's QoS requirement can be formulated as follows:

$$\begin{aligned}\max_{\boldsymbol{n}_i} \ R &= \sum_{i\in\mathcal{I}} r_i \\ &= \sum_k \sum_i n_i^k b_0 \log_2\left(1 + \frac{g_i^k p_i^k}{n_i^k b_0 N_0}\right) \quad \forall i \in \mathcal{I}\end{aligned} \tag{5.13}$$

subject to

$$n_i^k = 1, \ldots, M_k \quad \forall i \in \mathcal{L} \cup \mathcal{F} \tag{5.14}$$

$$\sum_i n_i^k \leq M_k \quad \forall i \in \mathcal{L} \cup \mathcal{F} \tag{5.15}$$

$$\sum_i p_i^k \leq P_k \quad \forall i \in \mathcal{L} \cup \mathcal{F} \tag{5.16}$$

$$p_i^k > 0 \quad \forall i \in \mathcal{L} \cup \mathcal{F} \tag{5.17}$$

$$\sum_i r_i^k \geq r_{\min}^k \quad i \in \mathcal{L} \tag{5.18}$$

The k-th InP provides M_k subchannels and the available amount of power is P_k. The first constraint indicates that the feasible space for the optimization problem is discrete and the second constraint states that the allocated amount of subchannels from k-th InP to all S_i ($i \in \mathcal{L} \cup \mathcal{F}$) should not exceed the total available subchannels. Similarly, Eq. (5.16) indicates that the overall transmission power from k-th InP to i-th slice should not exceed P_k while constraint (5.17) ensures that every S_i is assigned certain amount of power. The QoS requirement of the k-th InP is stated in constraint (5.18). $r^k_{\min}$ represents the minimum transmission rate requirement of the k-th InP which signifies the k-th InP is only willing to share the spare resources with S_i ($i \in \mathcal{F}$) when $\sum_i r^k_i (i \in \mathcal{L})$ is satisfied.

It is observed from Eq. (5.13) that it is an integer problem due to n^k_i is optimized in integer manner. This integer programming problem cannot be solved by the polynomial time-complexity algorithm [131]. To address this difficulty, constraint (5.14) can be relaxed into a continuous value by allowing n^k_i being a real number within $[1, M]$. Thus, constraint (5.14) can be written as

$$0 < n^k_i \leq M \quad \forall i \in \mathcal{L} \cup \mathcal{F} \tag{5.19}$$

In addition, let $b^k_i = n^k_i b_0$ which represents the amount of bandwidth that is allocated from k-th InP to i-th slice. Assuming each S_i is assigned the same amount of power, then p_i can be considered as a constant. Furthermore, constraints (5.16) and (5.17) can be eliminated. Therefore, Eq. (5.13) can be simplified as below

$$\max_{\boldsymbol{b}_i} \; R = \sum_k \sum_i b^k_i \log_2\left(1 + \frac{g^k_i p^k_i}{b^k_i N_0}\right) \quad \forall i \in \mathcal{I} \tag{5.20}$$

subject to

$$\sum_i b_i^k \leq B_k \quad \forall i \in \mathcal{L} \cup \mathcal{F} \tag{5.21}$$

$$b_i^k > 0 \quad \forall i \in \mathcal{L} \cup \mathcal{F} \tag{5.22}$$

$$\sum_i r_i^k \geq r_{\min}^k \quad i \in \mathcal{L} \tag{5.23}$$

By applying Lagrangian multipliers [132], the optimization problem in Eq. (5.20) is equivalent to finding the maximum value of the following function:

$$\begin{aligned} L = &\sum_{k \in \mathcal{K}} \sum_{i \in \mathcal{I}} b_i^k \log_2(1 + \frac{g_i^k p_i^k}{b_i^k N_0}) + \lambda_k (B_k - \sum_{i \in \mathcal{I}} b_i^k) \\ &- \sum_{k \in \mathcal{K}} \rho_k b_i^k + \sum_{k \in \mathcal{K}} \mu_k (\sum_{i \in \mathcal{L}} r_i^k - r_{\min}^k) \end{aligned} \tag{5.24}$$

where $\mathcal{K}$ is the set of InPs, λ_k, ρ_k and μ_k are the Lagrangian multipliers. To obtain the values of the multipliers, differentiate Eq. (5.24) respects to each multiplier and the dual problems can be solved by the gradient projection method. The update rules are

$$\lambda_k^{t+1} = \left[\lambda_k^t + \upsilon_k^t (\frac{\partial L}{\partial \lambda_k}) \right]^+ \tag{5.25}$$

$$\rho^{t+1} = \left[\rho_k^t + \nu_k^t (\frac{\partial L}{\partial \rho}) \right]^+ \tag{5.26}$$

$$\mu_k^{t+1} = \left[\lambda_k^t + \vartheta_k^t (\frac{\partial L}{\partial \mu_k}) \right]^+ \tag{5.27}$$

where $[\ ]^+$ denotes the projection of positive set, υ_k^t, μ_k^t and ϑ_k^t are the appropriate step sizes in iteration t. Different step size affects convergence speed where the convergence conditions are $\lambda^{t+1} = \lambda^t$, $\rho^{t+1} = \rho^t$ and $\mu^{t+1} = \mu^t$. By applying the Karush-Kuhn-Tucker (KKT) condition [133], it has

$$\begin{aligned}\frac{\partial L}{\partial b} =&(1+\mu_k)\Big[\log_2(1+\frac{g_i^k p_i^k}{b_i^k N_0}) \\ &- \frac{g_i^k p_i^k}{\ln 2(b_i^k N_0 + g_i^k p_i^k)}\Big] - \lambda_k - \rho\end{aligned} \tag{5.28}$$

In order to obtain the optimal b_i^k, the Newton's method [133] is applied to Eq. (5.28) beacuse it provides higher converges speed (the speed of convergence is illustrated below).

Function $f(n)$ can be represented by an expansion of a point which is close to the root of $f(n)$. Let n^* represents the root, the expansion can be written as

$$f(n^*) = f(n_i) + f'(n_i)(n^* - n_i) + T_1 \tag{5.29}$$

where

$$T_1 = \frac{1}{2!} f''(\vartheta_i)(n^* - n_i)^2, \quad \vartheta_i \in (n_i, n^*) \tag{5.30}$$

According to the Taylor's theorem [133], there is

$$\begin{aligned}0 = f(n^*) &= f(n_i) + f'(n_i)(n^* - n_i) + \frac{1}{2!} f''(\vartheta_i)(n^* - n_i)^2 \\ &= \frac{f(n_i)}{f'(n_i)} + (n^* - n_i) + \frac{f''(\vartheta_i)}{2f'(n_i)}(n^* - n_i)^2\end{aligned} \tag{5.31}$$

To rearrange the equation, it has

$$\frac{f(n_i)}{f'(n_i)} + (n^* - n_i) = -\frac{f''(\vartheta_i)}{2f'(n_i)}(n^* - n_i)^2 \tag{5.32}$$

From the Newton method, the n_i is calculated by

$$n_{i+1} = n_i - \frac{f(n_i)}{f'(n_i)} \tag{5.33}$$

Substitute Eq. (5.33) into Eq. (5.32)

$$n^* - n_{i+1} = -\frac{f''(\vartheta_i)}{2f'(n_i)}(n^* - n_i)^2 \tag{5.34}$$

Let $\varepsilon_{i+1} = n^* - n_{i+1}$ and $\varepsilon_i = n^* - n_i$, to take the absolute value of each side, then the above equation can be rewritten as

$$\mid \varepsilon_{i+1} \mid = \frac{\mid f''(n^*) \mid}{2 \mid f'(n) \mid}\varepsilon_i^2 \tag{5.35}$$

Since $f'(n_i) \neq 0$ and $f''(n)$ is continuous, Eq. (5.35) shows that the convergence speed is quadratic.

Let $f(b_i^k)$ as Eq. (5.28) and $h(b_i^k) = f'(b_i^k)$, there have

$$\begin{aligned} f(b_i^k) = (1+\mu_k)\Big[\log_2(1 + \frac{g_i^k p_i^k}{b_i^k N_0}) \\ - \frac{g_i^k p_i^k}{\ln 2(b_i^k N_0 + g_i^k p_i^k)}\Big] - \lambda_k - \rho \end{aligned} \tag{5.36}$$

$$h(b_i^k) = -\frac{1+\mu_k}{b_i^k N_0 \ln 2}\left(\frac{g_i^k p_i^k}{b_i^k N_0 + g_i^k p_i^k}\right)^2 \tag{5.37}$$

Then the value of b_i^k can be updated by

$$(b_i^k)^{t+1} = (b_i^k)^t - \frac{f(b_i^k)^t}{h(b_i^k)^t} \tag{5.38}$$

Property 1: The optimal subchannel value is converged by the Newton method.

Proof: In the optimal solution, the initial $(b_i^k)^0$ and all Lagrangian multipliers begin with arbitrary positive values. The Newton method will converge due to the concavity of the objective problem Eq. (5.13). Moreover, as Eq. (5.13) is concave and the objective value R increases in $(b_i^k,\ p_i^k)$ with fix g_i^k, it can be observed that R increases in b_i^k with fixed p_i^k and g_i^k. Therefore, by the Newton method, the objective function converges to the optimal value $\hat{b}_i^k$ regardless of the initial values $(b_i^k)^0$ and $(p_i^k)^0$.

With t iterations, the optimal bandwidth allocation $\hat{b}_i^k$ can be obtained. Furthermore, the optimal number of subchannel is $\hat{n}_i^k = \hat{b}_i^k / b_0$. The subchannel allocation algorithm is proposed below.

Algorithm 3 Subchannel Allocation Algorithm

Input: $(b_i^k)^0,\ (p_i^k)^0,\ (\lambda_i^k)^0,\ \rho^0,\ (\mu_i^k)^0,\ \boldsymbol{B}_k,\ \boldsymbol{g}_i^k,\ \boldsymbol{r}_{\min}^k$

1: **if** $\sum_i b_i^k \leq B_k$ **then**
2: update λ by
3: $\lambda_k^{t+1} = \left[\lambda_k^t + \upsilon^t (B_k - \sum_i b_i^k)\right]^+$
4: let
5: $f(b_i^k)^t = (1+\mu_k)\left[\log_2(1+\frac{g_i^k p_i^k}{b_i^k N_0}) - \frac{g_i^k p_i^k}{\ln 2 (b_i^k N_0 + g_i^k p_i^k)}\right] - \lambda_k$
6: and
7: $h(b_i^k)^t = -\frac{1+\mu_k}{b_i^k N_0 \ln 2}\left(\frac{g_i^k p_i^k}{b_i^k N_0 + g_i^k p_i^k}\right)^2$
8: update b_i^k by
9: $(b_i^k)^{t+1} = \left[(b_i^k)^t - \frac{f(b_i^k)^t}{h(b_i^k)^t}\right]^+$
10: **end if**
11: then $\hat{\boldsymbol{n}}_i^k = \hat{\boldsymbol{b}}_i^k / b_0$

This algorithm shows the process of gaining optimum subcahnnel allocation. It is states on line one that the total bandwidth assigns to foreign slices should not exceed the total band width B. Then the Lagrangian multiplier λ is introduced in order to solve this optimization problem. The allocated bandwidth is updated by line 9 and the process returns to line 1 which aims to find out if the total available bandwidth is fully allocated. The process repeats until the optimum value b is calculated and the number of allocated subchannel is obtained by line 11.

5.2.2 Power Allocation Algorithm

The previous subchannel allocation algorithm assumes that all local and foreign slices are assigned the same amount of power. Under this constraint, the optimum subchannel value is obtained. Assuming to the optimal subchannel assignment is $\hat{\boldsymbol{n}}_i^k$ that is obtaind by the subchannel allocation algorithm 3, then the optimal power allocation can be achieved. The power optimization problem is written as

$$\begin{aligned}\max_{p_i} \; R &= \sum_{i \in \mathcal{I}} r_i \\ &= \sum_{k \in \mathcal{K}} \sum_{i \in \mathcal{I}} \hat{n}_i^k b_0 \log_2(1 + \frac{g_i^k p_i^k}{\hat{n}_i^k b_0 N_0}) \end{aligned} \tag{5.39}$$

subject to

$$\sum_i p_i^k \leq P_k \quad \forall i \in \mathcal{L} \cup \mathcal{F} \tag{5.40}$$

$$p_i^k > 0 \quad \forall i \in \mathcal{L} \cup \mathcal{F} \tag{5.41}$$

$$\sum_i r_i^k \geq r_{\min}^k \quad i \in \mathcal{L} \tag{5.42}$$

Similarly to the subchannel allocation algorithm, the Lagrangian function of Eq. (5.39) can be written as follows:

$$\begin{aligned} L = &\sum_k \sum_i \hat{n}_i^k b_0 \log_2(1 + \frac{g_i^k p_i^k}{\hat{n}_i^k b_0 N_0}) + \beta_k (P_k - \sum_i p_i^k) \\ &- \sum_k \varsigma p_i^k + \sum_k \mu_k (\sum_i r_i^k - r_{\min}^k) \end{aligned} \tag{5.43}$$

Differentiate Eq. (5.43) respect of β_k, ς and p_i^k, the solution of finding Lagrangian multipliers is proposed in the subchannel allocation algorithm section.

$$\frac{\partial L}{\partial p} = \frac{g_i^k \hat{n_i^k} b_0 N_0 (1+\mu_k)}{\ln 2\left(\hat{n_i^k} b_0 N_0 + g_i^k p_i^k\right)} - \beta_k - \varsigma \tag{5.44}$$

$$\frac{\partial L}{\partial \beta_k} = P_k - \sum_i p_i^k \tag{5.45}$$

$$\frac{\partial L}{\partial \mu_k} = \sum_i r_i^k - r_{\min}^k \tag{5.46}$$

where the update rule of β_k is

$$\beta_k^{t+1} = \left[\beta_k^t + \omega_k^t (\frac{\partial L}{\partial \beta_k})\right]^+ \tag{5.47}$$

Thus, the p_i^k can be updated by the Lagrangian β_k

$$p_i^k = \hat{n_i^k} b_0 N_0 \left[\frac{1}{\ln 2(\beta_i^k + \varsigma)} - \frac{1}{g_i^k}\right]^+ \tag{5.48}$$

If the optimal dual solution Eq. (5.45) and Eq. (5.46) can be solved, the optimal primal variables can be obtained by Eq. (5.28) and Eq. (5.48). The power allocation algorithm is displayed in the following.

Algorithm 4 Power Allocation Algorithm

Input: $\hat{n}_i^k$, $(p_i^k)^0$, $(\beta_i^k)^0$, $(\mu_i^k)^0$, $(\omega_i^k)^0$, $\boldsymbol{P}_k$, $\boldsymbol{g}_i^k$, $\boldsymbol{r}_{\min}^k$, b_0

1: **if** $\sum_i p_i^k \leq P_k$ **then**
2: update β by
3: $\beta_k^{t+1} = \left[\beta_k^t + \omega_k^t(\frac{\partial L}{\partial \beta_k})\right]^+$
4: update p_i^k by Eq. (5.48)
5: **end if**

Based on the proceeding analysis, a joint power and subchannel allocation algorithm with QoS consideration for an WNV transmission system is provided below.

5.2.3 Joint Power and Subchannel Allocation Algorithm

The previous two sections provide a subchannel allocation and a power allocation algorithm. However, according to Eq. (5.1), it is clearly that the transmission rate varies with both power and sunchannel. In addition, the relation between power and subchannel is shown in Eq. (5.48). Namely, p changes accordingly when n changes and vice versa. Therefore, a joint power and subchannel allocation algorithm is proposed below.

$$\max_{\boldsymbol{n}^*,\boldsymbol{p}^*} R = \sum_{k\in\mathcal{K}} \sum_{i\in\mathcal{I}} n_i^k b_0 \log_2(1 + \frac{g_i^k p_i^k}{n_i^k b_0 N_0}) \tag{5.49}$$

subject to

$$\sum_i n_i^k \leq M_k \quad \forall i \in \mathcal{L} \cup \mathcal{F} \tag{5.50}$$

$$\sum_i p_i^k \leq P_k \quad \forall i \in \mathcal{L} \cup \mathcal{F} \tag{5.51}$$

$$\sum_i r_i^k \geq r_{\min}^k \quad i \in \mathcal{L} \tag{5.52}$$

$$n_i^k > 0 \quad \forall i \in \mathcal{L} \cup \mathcal{F} \tag{5.53}$$

$$p_i^k > 0 \quad \forall i \in \mathcal{L} \cup \mathcal{F} \tag{5.54}$$

Define vectors $\boldsymbol{n} = [n_1^1 \dots n_i^1, n_1^2, \dots n_i^k]$ and $\boldsymbol{p} = [p_1^1 \dots p_i^1, p_1^2, \dots p_i^k]$. Introduce the non-negative Lagrangian multiplier vectors λ, β, μ to the constraints, and the Lagrangian becomes

$$
\begin{aligned}
&L(\boldsymbol{n}, \boldsymbol{p}, \lambda, \beta, \mu) \\
&= \sum_{k\in\mathcal{K}} \sum_{i\in\mathcal{I}} n_i^k b_0 \log_2(1 + \frac{g_i^k p_i^k}{n_i^k b_0 N_0}) + \lambda_k (M_k - \sum_{i\in\mathcal{I}} n_i^k) \\
&+ \beta_k (P_k - \sum_{i\in\mathcal{I}} p_i^k) + \sum_{k\in\mathcal{K}} \mu_k (\sum_{i\in\mathcal{L}} n_i^k b_0 \log_2(1 + \frac{g_i^k p_i^k}{n_i^k b_0 N_0}) \\
&- r_{\min}^k) - \sum_k \varphi n_i^k - \sum_k \psi p_i^k
\end{aligned} \tag{5.55}
$$

Observe that for a given (λ, β, μ), the optimization problem in Eq. (5.55) consists of two sets of variables: subchannel n_i^k and power p_i^k for $i \in \mathcal{L}$, n_i^k and p_i^k for $i \in \mathcal{F}$. Let

$$
\begin{aligned}
D_1 &= \sum_{k\in\mathcal{K}} \sum_{i\in\mathcal{F}} n_i^k b_0 \log_2(1 + \frac{g_i^k p_i^k}{n_i^k b_0 N_0}) + \lambda_k (M_k \\
&- \sum_{i\in\mathcal{F}} n_i^k) + \beta_k (P_k - \sum_{i\in\mathcal{F}} p_i^k) - \sum_k \varphi n_i^k - \sum_k \psi p_i^k
\end{aligned} \tag{5.56}
$$

$$
\begin{aligned}
D_2 &= \sum_{k\in\mathcal{K}} \sum_{i\in\mathcal{L}} n_i^k b_0 \log_2(1 + \frac{g_i^k p_i^k}{n_i^k b_0 N_0}) + \lambda_k (M_k \\
&- \sum_{i\in\mathcal{L}} n_i^k) + \beta_k (P_k - \sum_{i\in\mathcal{L}} p_i^k) \\
&+ \sum_{k\in\mathcal{K}} \mu_k \left(\sum_{i\in\mathcal{L}} n_i^k b_0 \log_2(1 + \frac{g_i^k p_i^k}{n_i^k b_0 N_0}) - r_{\min}^k \right) \\
&- \sum_k \varphi n_i^k - \sum_k \psi p_i^k
\end{aligned} \tag{5.57}
$$

Thus the optimization problem can be also written as $\max_{n,p} D_1 + D_2$. Similar to the subchannel allocation and power allocation algorithms, differentiate D_1 and D_2 respecting n and p, the dual optimization problem can be expressed as

$$
\begin{aligned}
&\frac{\partial L(\boldsymbol{n}, \boldsymbol{p}, \lambda, \beta, \mu)}{\partial n} = \frac{\partial D_1}{\partial n} + \frac{\partial D_2}{\partial n} \\
&= (1+\mu_k)\left[\log_2(1+\frac{g_i^k p_i^k}{n_i^k b_0 N_0}) - \frac{g_i^k p_i^k}{\ln 2(n_i^k b_0 N_0 + g_i^k p_i^k)}\right] \\
&- \lambda_k - \varphi
\end{aligned} \tag{5.58}
$$

$$
\begin{aligned}
&\frac{\partial L(\boldsymbol{n}, \boldsymbol{p}, \lambda, \beta, \mu)}{\partial p} = \frac{\partial D_1}{\partial p} + \frac{\partial D_2}{\partial p} \\
&= \frac{g_i^k b_i^k (1+\mu_k)}{\ln 2\left(n_i^k b_0 N_0 + g_i^k p_i^k\right)} - \beta_k - \psi
\end{aligned} \tag{5.59}
$$

There is a unique optimal solution $(\boldsymbol{n}^*, \boldsymbol{p}^*)$ of the Lagrange function $L(\boldsymbol{n}, \boldsymbol{p}, \lambda, \beta, \mu)$ for a given (λ, β, μ). Thus the dual function is every where continuously differentiable. The gradient of the dual function for (λ, β, μ) is

$$
\begin{aligned}
&\left(\frac{\partial L}{\partial \lambda}, \frac{\partial L}{\partial \beta}, \frac{\partial L}{\partial \mu}\right) = \left(M_k - \sum_{i \in \mathcal{I}} n_i^k, P_k - \sum_{i \in \mathcal{I}} p_i^k,\right. \\
&\left.\sum_{i \in \mathcal{L}} n_i^k b_0 \log_2(1+\frac{g_i^k p_i^k}{n_i^k b_0 N_0}) - r_{\min}^k\right)
\end{aligned} \tag{5.60}
$$

In addition, it can be solved by the gradient projection method, and the update rules are follows:

$$
\lambda_k^{t+1} = \left[\lambda_k^t + \upsilon_k^t (M_k - \sum_{i \in \mathcal{I}} n_i^k)\right]^+ \tag{5.61}
$$

$$
\beta_k^{t+1} = \left[\beta_i^t + \omega_i^t (P_k - \sum_{i \in \mathcal{I}} p_i^k)\right]^+ \tag{5.62}
$$

$$
\mu_k^{t+1} = \left[\mu_k^t + \vartheta_k^t (\sum_{i \in \mathcal{L}} n_i^k b_0 \log_2(1+\frac{g_i^k p_i^k}{n_i^k b_0 N_0}) - r_{\min}^k)\right]^+ \tag{5.63}
$$

As mentioned before, υ_k^t, ω_i^t and ϑ_k^t are the step size in iteration t. Consider the diminishing step size rule as

$$\begin{aligned}
&\sum_{t=1}^{\infty} \upsilon_k^t = \infty, \quad \sum_{t=1}^{\infty} (\upsilon_k^t)^2 < \infty \\
&\sum_{t=1}^{\infty} \omega_i^t = \infty, \quad \sum_{t=1}^{\infty} (\omega_i^t)^2 < \infty \\
&\sum_{t=1}^{\infty} \vartheta_k^t = \infty, \quad \sum_{t=1}^{\infty} (\vartheta_k^t)^2 < \infty
\end{aligned} \tag{5.64}$$

If the optimal dual solution can be obtain, the optimal primal variables can be obtained by

$$p_i^k = n_i^k b_0 \left[\frac{1}{\ln 2(\beta_i^k + \psi)} - \frac{1}{g_i^k} \right]^+ \tag{5.65}$$

where n_i^k can be found from the subchannel allocation algorithm. According to the preceding analysis, a joint power and subchannel allocation algorithm is illustrated below.

Algorithm 5 Joint Power and Subchannel Allocation Algorithm

Input: $(n_i^k)^0$, $(p_i^k)^0$, $(\lambda_i^k)^0$, $(\beta_i^k)^0$, $(\mu_i^k)^0$, $\boldsymbol{M}_k$, $\boldsymbol{P}_k$, $\boldsymbol{g}_i^k$, $\boldsymbol{r}_{\min}^k$

1: **if** $\sum_i n_i^k \leq M_k$ **then**
2: update λ and μ by Eq. (5.61) and Eq. (5.63)
3: let $f(n_i^k) = \frac{\partial L(n,p)}{\partial n}$
4: and $h(n_i^k) = f'(n_i^k)$
5: update n_i^k by
6: $(n_i^k)^{t+1} = \left[(n_i^k)^t - \frac{f(n_i^k)^t}{h(n_i^k)^t} \right]^+$
7: **end if**
8: **if** $\sum_i p_i^k \leq P_k$ **then**
9: update β_i^k and p_i^k by Eq. (5.62) and Eq. (5.65)
10: **end if**
11: repeat step 1 to 10 until $r_i^k = \hat{r}_i^k$
12: return the optimal $\boldsymbol{n}^*$ and $\boldsymbol{p}^*$

Firstly, the optimum values n_i^k are obtained by line 1 to line 7, the detailed process is shown in Algorithm 3. After gaining the optimal amount of subchannel, the allocated power p_i^k is calculated by line 8 to line 10. The data rate r_i^k is updated each iteration until it reaches the maximum. Therefore, the optimal values of subchannel $\boldsymbol{n}^*$ and power $\boldsymbol{p}^*$ are obtained.

Based on the optimality conditions for the WNV transmission environment, the joint power and subchannel allocation method over multiple InPs and VNOs is shown above. Notice that the optimal maximum value of r_i is not only determined by n_i but also p_i. Therefore, the algorithm shows the possibility and feasibility of a distributed method for the coexisting foreign slices when the local slice's requirement is satisfied and it shares spare resources.

5.3 Performance Evaluation

In order to evaluate the total data rate, a simplified WNV transmission environment consisting of one OFDMA-based InP and two VNOs is considered. It is assumed that the InP has total bandwidth of 20MHz and the maximum transmission power is 5W. In addition, a large scale path loss is considered. In comparison, a fixed resources allocation algorithm (FRA) is provided, namely regardless the requirement from VNOs and InP's QoS demand, VNOs are only assigned the same amount of power and subchannel. In addition, the proposed subchannel allocation algorithm (SAA) and power allocation algorithm (PAA) are considered.

FIGURE 5.2 shows the total data rate of four algorithms: FRA, SAA, PAA and JPSA. It is clearly that JPSA achieves higher data rate than others under the same SNR values. In each iteration, the algorithm obtains the optimal value of subchannel and power allocation. In short, according to the iteration of power and subchannel allocation, it can achieve the best performance. The PAA adopts optimal subchannel value $\boldsymbol{n}^*$, thus it obtains higher data rate than SAA. Because FRA assigns each slice the same amount

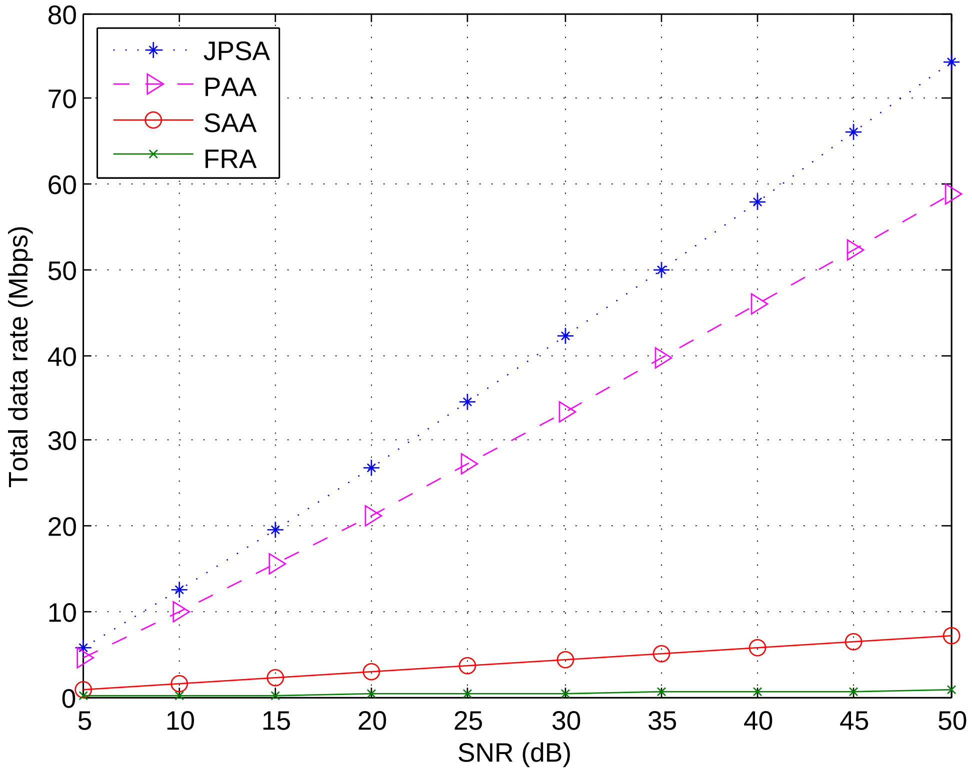

FIGURE 5.2: Total data rate of local and foreign slices

of subchannel and power, it has the worst performance. Therefore, it is more sensible to introduce a dynamic resource allocation algorithm.

It is shown in FIGURE 5.3 that total data rate varies according to the amount of total available bandwidth. Although the algorithm considers subchannel allocation, it more straightforward to display in terms of allocated available bandwidth. Apparently JPSA achieves the highest data rate while FRA remains the same value due to the subchannel and power assignment remains the same. In addition, apart from FRA, the rest algorithms obtain higher data rate when the total bandwidth increases. However, the amount of growth is relatively small. It because the SAA is the first step of JSPA while the initialization values are non-optimized. On the other hand, PAA adopt the optimum value of n^*, thus it performs better than SAA. To sum up, the total amount of bandwidth has less effect to the total data rate.

Followed by, the effect of the power amount has been evaluated. The result in FIGURE

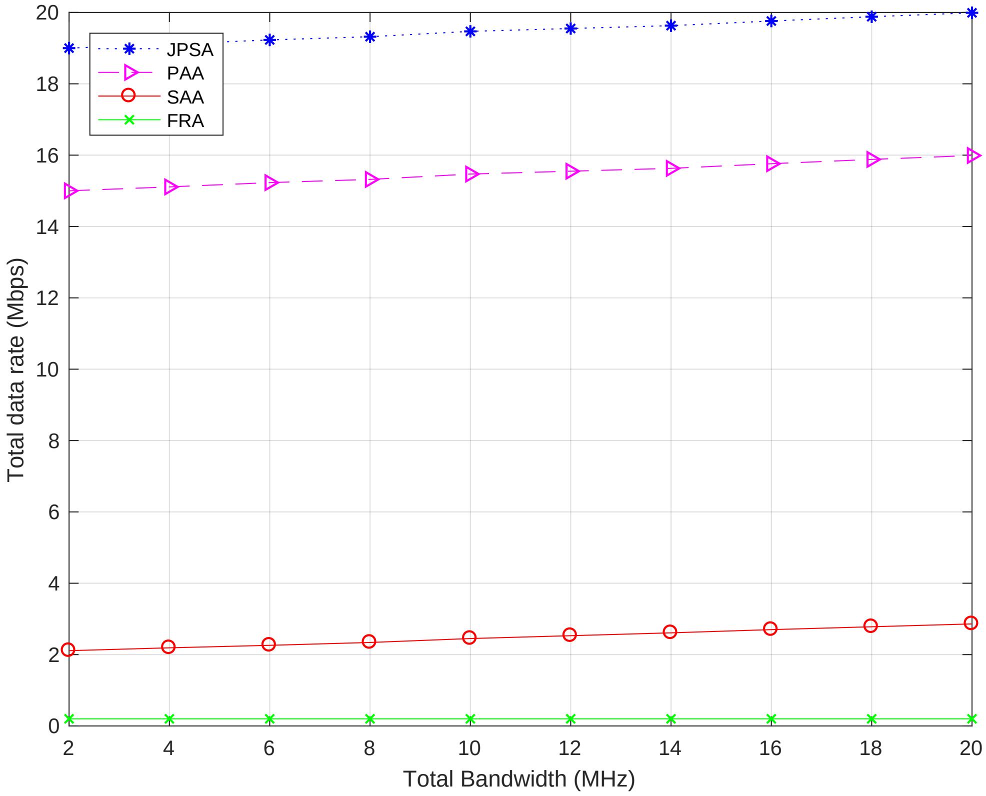

FIGURE 5.3: Total data rate vs. bandwidth

5.4 illustrates that the total data rate raises with higher power. Similar to the previous simulation, JPSA has the highest data rate while the FRA remains the same. In addition, it increases significantly with JPSA and PAA while only raises slightly with SAA. This is due to the SAA adopts the same power level for all slices. Accroding to Shannon limitation, to increase power level brings more interference to neighbouingr slices. However, due the the isolation of WNV, this change will not affect coexisting slices. Furthermore, the power constraint impacts the data rate more than the bandwidth constraint.

As mentioned before, the proposed JPSA considers the QoS requirement in terms of the data rate of the InP. FIGURE 5.5 displays when the QoS changes, how the foreign slices' data rate various. The data rate of FRA does remains the same because it assigns the same amount of power and subchannel to foreign slices regardless of local slice's demand. The foreign slices' data rate of SAA, PAA and JPSA decreases due to the

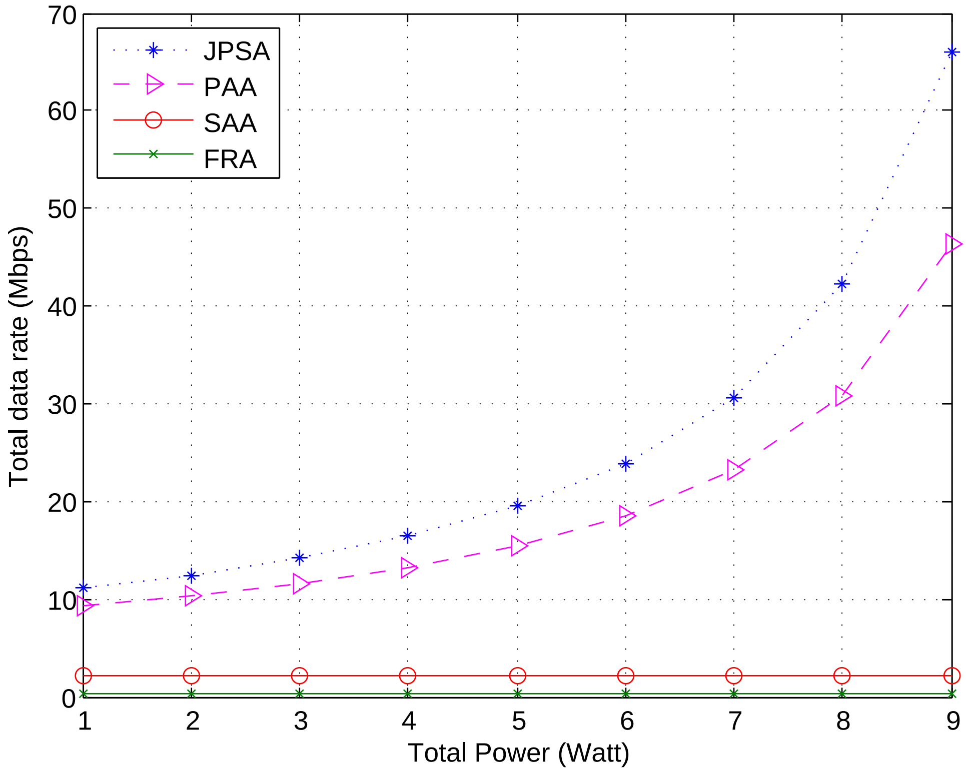

FIGURE 5.4: Total data rate vs. power

local slice's QoS requirement increases. In other words, less spare resources can be leased to foreign slices when the local slice's requirement increases. Thus, it leads to the reduction of foreign slices' data rate. If the local slice require majority of resources, it is more sensible to adopt SAA as it always has a certain amount of resources.

5.4 Summary

In this section, in order to achieve higher data rate, a joint power and subchannel allocation algorithm for the OFDMA-based WNV is proposed. This algorithm aims to maximize the total data rate of local and foreign slices with the QoS consideration. Namely, the local slice is only willing to share resources when its own request has been satisfied. The simulation results have shown that the proposed algorithm achieves higher data rate than the other benchmark algorithms. It is also been found that the power constraint has

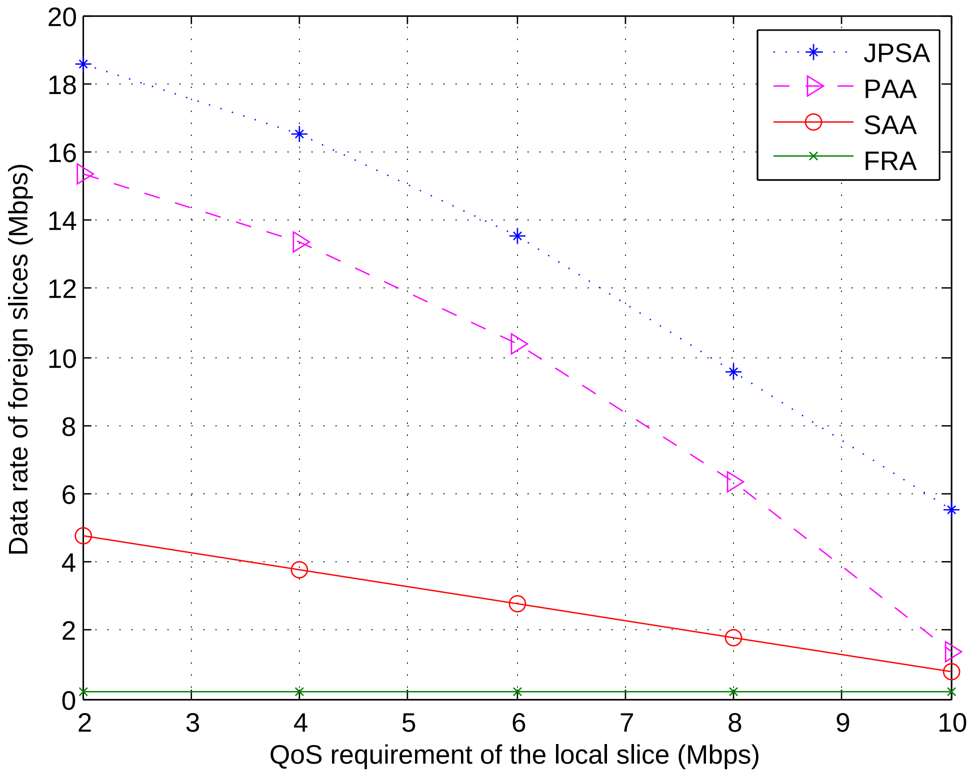

FIGURE 5.5: Foreign slices' data rate with different local slice's QoS requirement

more impact than subchannels. In another word, when total power level increases, the data rate raises dramatically whereas it increases slightly with higher total bandwidth.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

This thesis proposes three resource allocation algorithms for wireless network virtualization with QoS consideration in terms of the data rate. To the best of the author's knowledge, it is the first attempt to apply data rate constraint on OFDMA-based WNV transmission system. The power allocation algorithm is solved by gaming theory and the subchannel allocation algorithm is formulated to a binary integer programming. However, the results indicate that by using binary integer programming the overall throughput can be maximized but there might not consider the individual VNO's performance. On the other hand, by applying gaming theory, thought the total data rate cannot achieve the highest, the algorihm it balances the competition between VNOs. In addition, the joint resource allocation algorithm maximizes the total data rate as well as balancing the InP and VNOs. Although the algorithm is generated based on a single InP and multiple VNOs model, according to the mathmetic results that are provided in Chapter 3 to Chapter5, it can still apply the algorithm to any model. Based on the evaluation results, it can be found out that it is more sensible to using a joint allocation algorithm. Because the joint resource allocation provides higher resources efficiency.

Both power and bandwidth can be used effectively in order to increase users' satisfaction. In addition, the evaluation results also shows that the power amount has more effects to the system rather than the subchannel. To the best of the author's knowledge, the joint resource allocation algorithm adopts repeated iteration where it is hardly used in the current virtual resource allocation research.

To sum up, according to the simulation results, subchannel allocation has the least affect to the overall performance. However, it provides the best route to VNs. It means a VN who has the best channel quality would be assigned the most resources. Although the algorithm guarantees the minimum requirement of VNs, it cannot balance the benefits across VNs. The power allocation algorithm studies the energy efficiency problem. The evaluation results indicates that this algorithm cannot achieve the maximum data rate. Nevertheless, it maximizes the system energy efficiency as well as guarantees VNs balance. Finally, a joint resource allocation algorithm is proposed. Because it is more reasonable to consider multiple parameters in a practice work. The objective of this algorithm is to maximize the overall data rate as well as balancing the power of multiple VNs. By means of an iteration loop, the optimal assignments of power and subchannel are found. Moreover, the simulation results shows that power has more effects to the throughput than subchannel. In short, these analyses provide a guidance of choosing a suitable resource allocation scheme to a specific VN.

6.2 Future Work

WNV is a promising technology which enables resource sharing across physical entities and virtual entities. This thesis investegates resource allocation algorithms on WNV. However, in order to simplify the calucation, the proposed algorithm are all based on a one-InP-to-multiple VNOs model. This is only a special case in practice. As mentioned before, WNV enables VNOs borrow resources from different InPs. Thus it is more sensible to provide the multi InPs to multi VNOs system model where can be considered in the future. Based on the mathmetic simulation, it is possible to apply the algorithm to this system model. On the other hand, the simulation of this thesis is based on mathmetic analysis. Thus, deploying the algorithm onto a WNV test-bed can be considered in the future.

The simulation parameters are set under the boundary cases. Because the laboratory enviorment are limited, the author has no opportunity to apply the algorithms on a test-bed. It can be considered to deploy the algorithms on a test-bed in furture work. Moreover, the QoS requirment used in this thesis refers to data rate. Other QoS requests can also be considered such as bit error rate, delay, jitter and SNR. More QoS constraints complicate the algorithm. Nevertherless, it makes the algorithm more practical. There are more potential issues on WNV resource allocation can be studied while it is difficult to introduce all of them in this thesis. However, this thesis gives a general view of resrouce allocation algorithm design which benifits future works.

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