A Dynamic Spectrum Access Framework

(Bring Your Own Spectrum)

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To big Trippi, little Trippi, Shirley, and Humpty ball . . .

Declaration

DECLARATION OF ORIGINALITY

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Madhulika Tripathi
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Abstract

In this thesis, a unified and sustainable framework for spectrum allocation is presented. This multi-level operator-agnostic framework, Bring Your Own Spectrum (BYOS), is the result of a few thought experiments reflecting the ways in which spectrum could be bought and sold as an asset, similar to service models in cloud computing where every technical element can be traded via an "as-a-Service" model. BYOS architectural features form the major part of this thesis and cover four levels of abstraction as – contextual, conceptual, logical and physical.

First, the contextual aspect of BYOS is covered, which addresses the question: "*why is the framework needed?*". To understand the reasons behind the need for a new framework an exhaustive survey of history of telecommunications policy development of 32 countries was conducted that included major economies in several key regions of the world. This research provided insight into the role of the government, mechanisms used for allocations, success/failure of allocations, and business models in the sector. Additionally, a review of existing and emerging technologies was done to understand various possible mechanisms of spectrum access.

Next, the conceptual aspect of BYOS is presented, which addresses the question: "*what does the framework look like?*". For this, the information from the study above was converted into a skeleton framework, ensuring that it covers the requirements gathered. The framework has a three-level architecture with a quasi-static allocation scheme. The levels of architecture are designated based on periods of ownership and the thesis presents an original exponential-based-scale to determine the allocation periods (longest to shortest). The framework accommodates different types of operators, categorising in terms of their spectrum access privileges.

Following this, the thesis focuses on the physical level of the framework, where the question: "*with what?*" i.e. the technical mechanisms are discussed. In this part, a novel analogy is presented where the wireless spectrum is compared to a multi-lane, multi-level highway. This analogy provides the basis for unit of information transport between two points, which in turn form the trading unit. In this thesis, "Interference (transmission power) spread over bandwidth" is chosen as the basic trading unit for the BYOS framework. Also

included is a discussion on the required changes to the calculation of "population" – an inherent part of reserve price calculation – in view of the proliferation of device using different types of mobile technologies.

A second part of the physical framework presents an original mechanism for competition management in view of the new framework and trading unit. Using the principles of network traffic management, a new tracking unit – token – is introduced, which helps the regulators keep track of the process of spectrum allocation, but in a hands-off manner. Multiple models of using tokens in the framework are presented. Tokens are intended only for the short-term trades, though the initial number is determined by the total spectrum acquisitions and cumulative participation behaviour.

Finally, the logical or system model of the framework is presented, which addresses the question: "*how to structure and organise the architecture to achieve the desired requirements*". This discussion is also divided into two parts. First, the discussion focuses on the multiple ways to use tokens and demonstrates the different use cases by way of competition games. Key novel points here are the discussion of competition management over multi-period allocation and addressing the needs of public safety services. Additionally, the discussion also focuses on unequal desirability of available spectrum lots based on spectrum characteristics, acquisition periods, and operator's own requirements. The second part of the discussion focuses on various methods of implementation of this framework. A potential enterprise-blockchain based method is explored, though there may be other better solutions.

Another focus of this thesis, which can be considered as a separate minor segment, came out of the initial policy research was to organize and analyse this information systematically. For this purpose, the theory of policy diffusion was explored, and the research provides evidence for the existence of, and analyses the mechanisms used for policy diffusion in different regions and countries.

Table of contents

List of figures

List of tables

List of Abbreviations

Acronyms / Abbreviations

3GPP	3rd Generation Partnership Project
aaS	as-a-service
ABS	Australian Bureau of Statistics
ACA	Australian Communications Authority
ACMA	Australian Communications and Media Authority
AIP	Administrative Incentive Pricing
AM	Analog Modulation
AMC	Albanian Telecom
ASA	Authorised Shared Access
ASX	Australian Stock Exchange
AUSTEL	Australian Telecommunications Authority
AWS	Advanced Wireless Services
BBC	British Broadcasting Corporation
BT	British Telecom
BTC	Bulgarian Telecommunications Company
BTCL	Bangladesh Telecommunications Company Limited
BTO	Build-Transfer-Operate

BTU	Basic Trading Unit
BYOS	Bring Your Own Spectrum
CaaS	Capacity-as-a-service
CAI	Common Air Interface
CBI	Central Bureau of Investigation
CBRS	Citizens Broadband Radio Service
CCA	Combinatorial Clock Auction
CDMA	Code-division Multiple Access
CEE	Central and Eastern European
CoCom	Coordinating Committee for Multilateral Export Controls
CRTC	Canadian Radio-Television and Telecommunications Commission
DaaS	Data-as-a-service
DAG	Directed Acrylic Graph
DBT	Deutsche Bundespost Telekom
DLT	Distributed ledger technology
DoT	Department of Telecommunications
ETSI	European Telecommunications Standards Institute
EU	European Unionp
FCC	Federal Communications Commission
FDD	Frequency Division Duplexing
FinTech	Financial technology
FM	Frequency Modulation
FRC	Federal Radio Commission

GAA	General Authorised Access
GPO	General Post Office
GSM	Global System for Mobile Communications
GSMA	GSM Association
IaaS	Infrastructure-as-a-service
ID	Identifier
IMT	International Mobile Telecommunications
IoT	Internet of Things
IP	Internet Protocol
ITL	Interference Temperature Limit
ITU	International Telecommunications Union
LoRa	Long Range
LSA	Licensed Shared Access
LTA	Long-term Allocations
LTE	Long-Term Evolution
M2M	Machine-to-Machine
MNO	Mobile Network Operator
MTA	Medium-term Allocations
MTC	Machine-Type Communications
MVNO	Mobile Virtual Network Operator
$NB-IoT$	Narrowband Internet of Things
NTC	National Telephone Company
NTP	New Telecom Policy

OfCom	Office of Communications
OTC	Greek Telecom
OTC	Overseas Telecommunications Commission
PAL	Priority Access License
PCS	Personal Communications Services
PFD	Power Flux Density
PMG	Post Master General
PSTN	Public switched telephone network
PU	Primary User
QoS	Quality of service
R&D	Research and development
RegTech	Regulatory technology
RF	Radio Frequency
RMS	Royal Mail Ship
RSPG	Radio Spectrum Policy Group
RT	Romtelecom
SaaS	Spectrum-as-a-service
SAS	Spectrum Access System
SCA	Simple Clock Auction
SFR	Société française du radiotéléphone (SFR)
SIGET	Superintendencia General de Electricidad y Telecom
SINR	Signal-to-interference-plus-noise ratio
SLC	Subscriber-Linked Criterion

SMA	Spectrum Management Agency
SMR	Simultaneous Multi Round
SMRA	Simultaneous Multiple-Round Auction
SPTF	Spectrum Policy Task Force
SS	Steam Ship
STA	Short-term Allocations
SU	Secondary User
TASF	Technical Application Suitability Factor
TDD	Time Division Duplexing
TDMA	Time-division Multiple Access
TNR	Transfer Notification Register
TUF	Titulo de usufructo de frecuencia
UASL	Unified Access Service License
UK	United Kingdom
UL	Unified Licensing
UMTS	Universal Mobile Telecommunications System
US	United States
USO	Universal Service Obligations
VCG	Vickrey-Clarke-Groves
VSNL	Videsh Sanchar Nigam Limited
WTO	World Trade Organization

Preamble

This thesis is not the outcome of a single, unitary research project. Instead, it contains the results of examining a problem from multiple perspectives expressed in the form of a framework.

The central purpose of my research is to develop a unified and sustainable framework for spectrum assignment. This discussion, by definition, encompasses the questions – who to allot, when to allot, what to allot, and how to allot. In an effort to find satisfactory answers to these questions, my research has taken me to thoroughly study telecommunication policies, analyse the economics of operating commercial mobile networks, and research-and-review various radio communication network technologies. Additionally, the work also includes aspects of game theory and blockchain technology, to answer the "how to assign" question. The technical components of this work, though diverse, are naturally compatible as logical extensions and hence do not require a comprehensive overview. However, the individual decisions such as choosing a particular mechanism/technology, allowing specific levels of data transparency/immutability, selecting specific license ownership periods etc. were based on the information gathered from a research into historical telecommunications policies. As this work is fundamentally different in nature to technical part of the framework, this preamble explaining the contents of the thesis and organization is given.

0.1 Research premise and questions

The initial hypothesis of the research was that *the widespread adoption of personal mobile radio technologies would soon lead to wireless spectrum scarcity*. This was the basis of the research question **How to trade/share spectrum based on dynamic demand, without intervention from the regulator i.e. bilaterally?** This eventually led to the idea of including variable time periods and different operator types as part of the framework. Because the framework address dynamic spectrum ownership, lowering barriers for new entrants is also a related motive.

The notion of spectrum scarcity was based on the use of the term "spectrum crunch" in available literature. The term "spectrum crunch" was a part of an official Federal Communications Commission (FCC) report [7]. This report also suggested that the means of assigning spectrum were inefficient, which was also corroborated by research experiments conducted in 2005 [8]. Both reports suggested that spectrum assigned to existing users, on a long-term basis, was not efficiently used. This unused part of the spectrum could be assigned to interested users by existing owners.

An initial background research of the spectrum assignment history (focused on US at this point) showed that the "crisis" in the context of spectrum assignment was used for the first time in 1920s [9, 10], partly disproving the hypothesis that the scarcity was only due to growth in the number of wireless users, though it was connected. These research reports [9, 10] also pointed out that that the development of formal policies into spectrum management were mostly ad-hoc and reactive based on public sentiments of the time. This led to the initial research into US spectrum policy history. To determine the attitude of other countries, the historical policy research was extended. The purpose was to determine the reasons behind ad-hoc or adopted policy making, to ensure that the current work included measures to avoid this eventuality. The research question remains the same, but the solution (i.e. framework for assignment) required studying the issue from multiple perspectives – policy, economic and technical.

0.2 Thesis Organisation

This thesis can broadly be divided into three parts (followed by the conclusion in Chapter 7):

- Part I (Chapters 1 and 2) – Policy and economics research results, used to develop the Contextual (Scope) and Conceptual (i.e. Business) model of the framework. Policy analysis to understand how governments develop policy was extensively researched and the results are presented in Chapter 1. In Chapter 2, the information from the research conducted is used to propose the new framework for spectrum assignment.

- Part II (Chapters 3 and 4) – Technical research outcomes, used to develop the Physical (i.e. Technology model) design of the framework. Two elements of physical design are covered – the trading unit used within the framework (instead of spectrum frequency channels) covered in Chapter 3; and the mechanism for ensuring fair competition in the spectrum markets covered in Chapter 4.

- Part 3 (Chapters 5 and 6) – Consolidating the framework to build the Logical (i.e. Systems model) architecture of the framework. The systems model is presented in two parts – interaction between participants within the framework as buyers, sellers and the regulator covered in Chapter 5; automated framework management in terms of information flow between the participants of the framework covered in chapter 6.

Chapter 6 is followed by the final Chapter 7, where a summary of the research is presented. In this chapter the research contributions are discussed along with their implications and future work areas that arise from these contributions.

0.3 Key contributions

The thesis makes the following contributions:

- Theoretical review and analysis of telecommunications policy development in key countries and regions of the world (32 countries were covered as part of the research).
- Provide evidence of the existence of policy diffusion at key (common) periods of telecommunications policy change – initial policy development, liberalisation, and adoption of market mechanisms (auctions) to assign spectrum. The mechanisms of policy diffusion used by countries were also found and presented.
- Propose a new framework for spectrum assignment that allows spectrum to be owned for different periods and allows multiple operators to coexist within the same frequency band.
- Define a trading unit for assignment that allows spectrum to be shared between operators.
- Propose a novel network-traffic-management based competition management mechanism – the token.
- Illustrate the use of the proposed mechanisms to allow priority access to spectrum for public safety services
- Illustrate mechanisms to allow multi-period assignment. Currently assignment within a country is usually done for a fixed period of time (exceptions are when spectrum lots remain unsold).

- Illustrate how digital ledger technologies and smart contracts can be used for implementing the framework.

0.4 List of Original Publications

The work done as part of this thesis has resulted in the following papers (including some that in process)

- Tripathi M, Phillips B, Sorell M, (2019), Bring your own spectrum (BYOS): A tiered architecture supporting flexible spectrum assignment, 30th European Regional ITS Conference: Towards a Connected and Automated Society, Helsinki, Finland, 16th-19th June, 2019
- Tripathi M, Phillips B, Sorell M, (2019), The need for a new spectrum framework for future spectrum management: Background to the BYOS framework, 14th Phd Seminar, 30th European Regional ITS Conference: Towards a Connected and Automated Society, Helsinki, Finland, 16th-19th June, 2019
- Paper in Progress: Tripathi M, Phillips B, Sorell M, (2020), A framework to incentivise technology-agnostic sharing/trading of spectrum over flexible time periods
- Paper in Progress: Tripathi M, Phillips B, Sorell M, (2020), Spectrum trading using power-based trading rights
- Paper in Progress: Tripathi M, Phillips B, Sorell M, (2020), A novel mechanism for incentivising spectrum sharing with hands-off regulatory oversight to ensure fairness

Chapter 1

Background

This chapter covers the theoretical background of this thesis. It starts with a discussion on the origin of spectrum regulation and then presents the rationale behind the development from origin to the present. The key factors affecting the policy are introduced chronologically, followed by a discussion on the theory behind the mechanisms for policy change during the period. Next, a historical overview of telecommunications regulations of countries from several regions of the world are explored in some detail. The study focuses on specific changes and events that affected the telecommunications policy of each country covered in the discussion. The results from this study are then summarised and analysed in the context of the theory for policy adoption giving the basis of the design of the framework.

1.1 Origins of radio spectrum regulation

1.1.1 Titanic marks the true beginning

On April 14 1912, RMS Titanic, a British passenger liner sank after hitting an iceberg in the mid-Atlantic [11, pg. 213]. This is considered to be one of the worst among modern maritime disasters, and not entirely because of the number of casualties. The ship famously had multiple safety mechanisms, all of which failed to avert the disaster, and were subjected to intense public scrutiny at the subsequent enquiries. In his book, Kovarik [11, pg. 213] mentions that, of the two major enquiries set up to investigate the incident, the UK-based enquiry absolved Marconi (with reservations) stating that saving about 700 lives that were saved would not have been possible without the radio – true as RMS Carpathia only rushed to the rescue after receiving the radio message. However, the US-based enquiry pointed out that 1500 lives perished because the nearest ship SS Californian did not hear the radio message for over 4 hours.

There were two key issues with the use of radio communications equipment aboard the Titanic – technological and regulatory – both high relevant to the future development of radio communications. These issues also form the core rationale behind the novel framework for spectrum allotment and management proposed in this thesis.

Interestingly Titanic's infamy comes from the ill-advised boast of being the *unsinkable ship* [12, pg. 19]. It was touted as the most modern ship of its day equipped with the best possible technologies on board, including a wireless radio. However as Kovarik [11, pg. 213] points out, the claims weren't correct, at least in the context of radio communications technology used on the ship. The radio onboard the ship was said to have known bandwidth problems causing interference to all ships in the signalling distance. In most of the transatlantic ships during the time, including Titanic and surrounding ships, the communications equipment used onboard was the latest Marconi radio system – developed in 1897 [12, pg. 19]. However, Kovarik [11, pg. 213] contends that the *spark* technology had already been superseded by better systems developed in US and Europe. He also adds that Marconi used a combination of patents, regulations and monopoly to ensure that the technology used essentially remained obsolete, and as a consequence, dangerous.

From the regulatory perspective, the situation brought the tussle between commercial radio operators and the government to a head. While commercial operators understandably had profitability and universal domination as their objectives, as Medoff and Kaye [12, pg. 19] point out, the government wanted to bring the radio under strict federal control. The reason, according to them, was that the rising popularity and advances in radio technology suggested its immense potential in the areas of defence, health and safety. The two enquiries, mentioned above, actually highlighted this point and that a measure of oversight was definitely required to balance commercial interests with public interest.

As mentioned in the introduction, the basic premise of this thesis is that key regulatory policies in the telecommunications sector, during and post the 1912 Titanic incident, were proposed as a reactive measure. Building on this premise, we have two foci. The first is to understand the conditions under which countries engage in policy adoption. The second one is to understand mechanisms of diffusion used for policy adoption. The results from the present work are used for developing the framework for spectrum assignment using an enterprise architecture framework. The discussion leading up to the proposed framework is covered in two chapters. This chapter presents the summary and results of the exploratory research conducted to support the hypothesis. Chapter 2 discusses other reasons for needing a new framework and introduces the skeleton architecture of the framework.

1.1.2 Rationale behind the current wireless spectrum policy landscape

This section introduces the premise developed as a result of the exploratory theoretical research of the spectrum assignment policies of multiple countries.

As this part is the theoretical research, the results are implied by the actions taken at the time. Figure 1.1 below shows the analysis timeline that has been used as a common framework to present the key policy decisions of the countries under consideration. This is a cause-and-effect timeline that also depicts salient factors that have shaped the telecommunications policy. Using this framework, a comprehensive and systematic review of telecommunication policies of 35 countries was conducted. The rationale behind choosing the countries was to select the major economies from the key geographical regions of the world – North America, South America, Western Europe, Central & Eastern Europe, Asia, Oceania, and Africa. It is shown through discussions that the current wireless spectrum policy landscape is a result of multiple changes in business ownership structures and resource assignment models. Despite the fact that some of changes have been very drastic and fundamental, the centralised and ad-hoc mode of spectrum assignment has remained unchanged. The purpose of the exploratory research was to find evidence for the research hypothesis that ***the governments did not make an effort to develop proactive policies for spectrum assignment involving informed consensus from all concerned parties***. The discussions also show that key policy decisions were a result of knee-jerk reactions to prevailing public sentiment to specific events. The thesis postulates that this form of policy development is why the regulations seem to

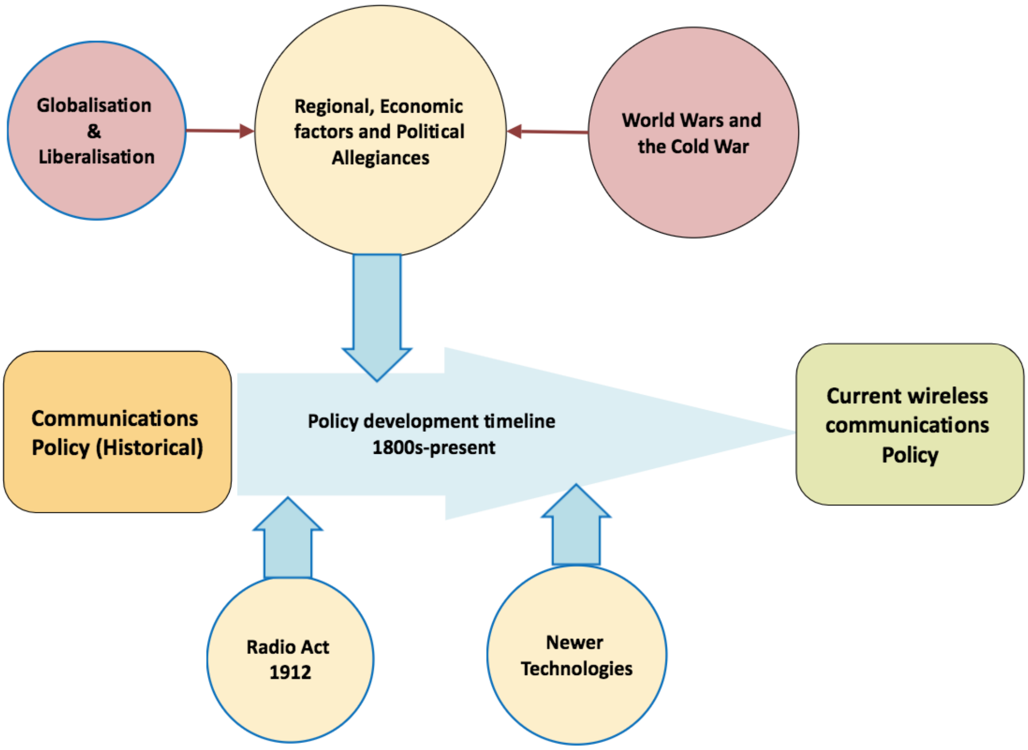

Fig. 1.1 Timeline view of the factors that shaped telecommunications policy

be forever behind technological developments. The current regulatory framework requires changes given the unprecedented rise in wireless service demands in the present coupled with technical advancements and a need for existence of multiple services and operators in the same frequency band.

Based on research (discussed in subsequent sections) major changes in wireless-based telecommunication policies in a country took place as a reaction to four key events given below:

- The 1912 Radio Act
- Liberalisation of telecommunications sector in 1980s
- The 1989 Revolutions in Central and Eastern Europe
- Active adoption of 2G mobile technology in 1990s

These events were interestingly found to be common to almost all the countries that were analysed. Policies in the US were not impacted by telecommunications liberalization in 1980s or the 1989 revolutions. However, the US had started to experiment with new spectrum assignment mechanisms in 1980s and by 1990s had started to question the command-and-control model of spectrum management [7], showing that these periods were significant to the US, and by extension, other countries in North and South America as well. In most countries in South America, Central & Eastern Europe, Asia, and Africa the liberalization process started in 1990s, as a direct consequence of the 1980s liberalization in Western Europe and post the fall of Communism in later 1980s (discussed in section 1.3). So while 1980s were fairly uneventful, most countries (apart from US and Western European nations) dealt with the impact of both liberalization and globalization in 1990s.

The discussion presented in the rest of this chapter has the following structure. First, the impact of the 1912 Radio Act on the need for unification in government spectrum management policies is covered in section 1.1.3. This is important, because it underlines the need for the development of a global policy body i.e. the International Telecommunications Union (ITU) and touches on the restrictions caused by such a need. Next, the policies of the countries surveyed are traced from early 1900s until early 2000s, highlighting key events that have shaped individual policies. Countries having major impact on the telecommunication policy landscape or with interesting policy elements are covered individually and in greater detail in section 1.2. Policies of remaining countries in the survey are discussed in section 1.3 as regional groups to trace the impact of adopted policies on smaller countries. While studying these impacts, mechanisms of how policy diffused between different countries and regions also became clear. This is important because any future spectrum management framework needs to be adapted keeping in mind both local factors and the need to adhere to global standards. These mechanisms are discussed in section 1.4.

1.1.3 Impact of the 1912 Radio Act

Attempts to regulate wireless communications began in earnest in the 1890s. Telecommunications regulatory structure itself grew from a shared legacy with the general communications sector. Because of the nature of the services, the regulation naturally fell in with the department regulating postal and wired telephone communications. In countries with a strong central government like Germany, France and the United Kingdom, the services were regulated centrally [13–15] while in countries like Australia, Canada and the US, which comprised of strong independent states, the regulation was carried out by the local authorities [16–18]. At the time licensing regulations and central oversight was not a part of the wireless spectrum landscape though the government agencies had understood the importance of international agreements on the usage of wireless technologies. In fact, prior to 1912, most commercial wireless devices were onboard ships and the only regulatory requirements was for these devices to be able to communicate with coastal stations and other ships within the range. The initial efforts to translate these requirements into formal regulations are summarised below:

- The first international telecommunications conference (technically pre-conference) took place in1903 in Berlin to discuss the development of common radio standards[1].The outcome of the conference was the development of the first international radio communication standards. The purpose was to ensure that coastal stations would be able to send and receive all wireless transmissions from ships at sea, regardless of the specific system used. Priority was to be given to ships in distress. Not all countries agreed to the provisions but it was a landmark effort to put in regulations in this area [19].
- The 1904 Roosevelt Board report was the first to recommend coordination between the developments of radio services by different government agencies in the US. The report was also the first to recommend government oversight by a single department (in this case Navy) and significant restrictions on commercial stations when they conflicted with government operations [20, p. 76]. There were two interesting aspects of these incidents: the push by commercial operations to retain their monopoly of the services, and push by the government agencies to centralise the control of operations [19].
- The official international telecommunications conference was held in 1906 in Berlin. The purpose of the conference was to expand the issues covered in the 1903 conference. This resulted in the first official international agreement that all ships must be able to communicate with each other regardless of the technology, even when there is no emergency [2] [19].
- The idea of introducing federal licenses for all radio stations was first proposed in 1908 in the US Senate. The Hale Bill of 1908 also introduced the idea that the President would be at liberty to abolish all the licenses during wartime. The bill and three subsequent amendments were never voted upon despite the support of President Roosevelt as the commercial interests were sufficiently powerful to forestall legislations. The 1908 editorial by Electrical World commenting on the Hale Bill was the first that suggested that centralised control of radio communications was not a

[1]Curiously this conference was also caused by Marconi company's policy denying communications from ships using other company radio. [19]

[2]The United States was, at the time, the only country fully in favour of this idea. White other countries agreed on the principle of compulsory communications between shore and ships, technology-neutrality became a hotly contested topic of debate. Eventually, the idea was deferred for discussion at the next summit

good idea given that it was such a new field and new technologies were just around the corner. Interestingly this statement holds true about wireless technology today and for the foreseeable future suggesting that legislations in this area should be flexible enough to accommodate for future changes [21, pg. 130-131].

- The discussions building up to this point led to the the development of the 1910 Wireless Ship Act. This was the first major radio communications legislation requiring all major vessels of all nationalities visiting the US regardless to install radio equipment by July 1, 1911. This essentially meant that it was illegal now to ignore or refuse relaying messages from another ship using another company's equipment [19].

Titanic, having complied with the latest 1910 Ship Act, was deemed safe even when the worst happened. The background is important because it gives the context under which spectrum regulation started to emerge. The motivation of the government was to control the operation and open a new area of revenue. Private services, in general, were more interested in increasing their area of influence and extending the shelf life of existing technology. Innovators and those in academia had solutions to existing limitations, but lacked the clout to get the new technology adopted.

When Titanic sank on April 15, governments gained a significant edge over the commercial interests, under the notion of *common good*. This led to the centralised regulation approach that is followed even today. Even in countries where market–based mechanisms are used, governments maintain a highly interventionist approach in the telecommunications landscape. The main issue with the 1912 Act was that this was a bandaid solution developed in a hurry – the draft was proposed in the London convention in June 1912, the new regulations were signed by the US President Taft on August 13 and by December 13 the legislation came to effect officially implementing the original provisions of the 1906 Berlin convention [19].

The central provision of the 1912 Radio Act was to enforce the practice of acquiring licenses to operate by any non-governmental party. The law also compelled radio stations to stick to a particular wavelength while transmitting and receiving. The Radio Act immediately brought all the radio communications under governmental control as both commercial stations and amateurs were obliged to seek permission to operate and not interfere with any government radio operations [19]. This in fact created the precedent for the development process of telecommunications policy in the US – developed in a rush, reactive, non-consultative, highly centralized and prescriptive. It wasn't until the 1980s that the regulators factored in market-based competition while developing wireless spectrum policies. It must be also noted that while most of the provisions set by the U.S. 1912 Radio Act have changed, the basic tenet of private radio operators requiring fee-based licenses (not property rights) to operate, continues to apply. The licenses are assigned, defined and regulated by the United States government, though local authorities are responsible for actual spectrum management. [7]

1.1.4 Policy diffusion

While analysing the policies of countries, a clear pattern emerged of the interdependent nature of policy making between countries. Licensing was not a new concept in telecommunications and by 1880 was already being used in some European countries like Germany, France and UK [13–15]. The US and Canada provided the opposing viewpoint with patent-based commercial market mechanisms [17, 18]. However, the fact that there was a push towards an international policy conference even at the earliest stages of technology development, shows that it was considered as an essential service.

The interesting and unique aspect of regulation in telecommunications was however the push to standardise the regulations and coerce countries to negotiate and collaborate with each other to set up common regulations. However, different countries developed proprietary solutions and international agreements such as push to harmonisation were guided more due to commercial interests than by government regulations [22]. The earliest formal instance of this in wireless communications sector can be seen at the 1906 Berlin conference discussed above. Ironically, the precursor to both these was Marconi and his view to standardise equipment on all ships and across international border to ensure commercial success.

This phenomenon of policy interdependence is recognised and termed as ***policy diffusion***. As a brief background, the term *diffusion* was introduced in the socio-political context by Strang [23] in 1991, partly to explain the decolonization process of British and French colonies that happened almost *en masse* post the Second World War in 1945. In 2006, Simmons, Dobbin and Garret expanded the definition given by Strang and extended it to state: *policy diffusion occurs when government policy decisions, in a given jurisdiction, are systematically conditioned by prior policy choices made in other jurisdictions* [24]. The definition was further extended by Shiplan and Volden [25] in 2012 to expand the idea from policy diffusion between jurisdictions to diffusion between state and federal level governments and also in the international context between the European Union and its member states. In 2016, Wavre [26] used policy diffusion in the telecommunications regulation landscape for the first time by assessing the diffusion between Middle Eastern and North African countries – specifically Jordan, Morocco and Egypt.

Of these works, Shiplan and Volden provide the most pragmatic outlook for the concept of policy diffusion – not only explaining what the idea means, but also stating the limitations and conditions. Policy diffusion is clearly stated to be not always a beneficial idea and that it is dependent on individual government capabilities and the policies themselves [25]. Figure 1.2 below shows the mechanisms by which policy diffusion can occur and the indicators of whether this is a good idea or not. This representation is a slight modification to the structure provided by Maggetti and Gilardi [27] in their paper. While every imitation or coercion doesn't indicate a policy failure, the act of imitation or coercion does imply that other relevant factors have probably not been considered during policy implementation.

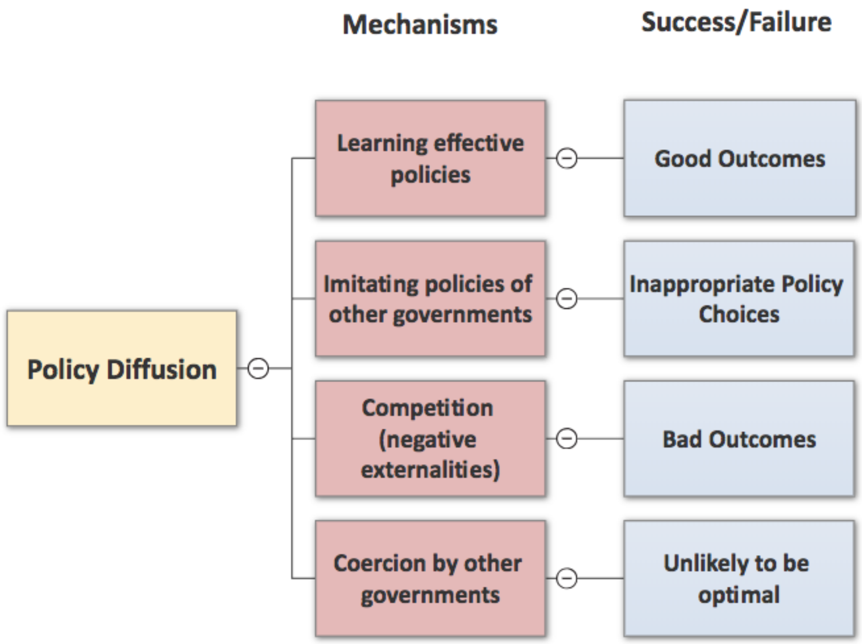

Fig. 1.2 Policy diffusion mechanisms (adapted from [27])

The framework shown in figure 1.2 for policy diffusion has been used to conduct an exploratory study of spectrum management in different countries. As will be shown, within the telecommunications landscape, most countries have chosen to emulate a selected few in terms of best practices to be followed for regulating and managing wireless spectrum. Unsurprisingly, countries leading the way in terms of telecommunications regulation – the US, the UK, Germany and France – were participants of the 1906 Berlin conference. There are multiple examples of policies that were almost entirely imitated, specifically during telecommunications liberalisation and while selecting mechanisms used for spectrum assignments. The success or failure of the emulated policy decisions has been found to be dependent on the mechanisms used.

Building on this premise, we have two foci. The first is to understand the conditions under which countries engage in policy adoption. The second one is to understand mechanisms of diffusion used for policy adoption. The results from the present work are used for developing the framework for spectrum assignment using an enterprise architecture framework. The policy reviews in section 1.2 evaluate the conditions and mechanisms.

1.2 Country/region specific overview

In this section, a historical overview of telecommunications regulations is presented. The discussion begins with historical telecommunications policy regulation in the the US. This is covered in some detail because reasons behind the success and failures of individual policy mechanisms were observed and emulated throughout the world, independent of their actual adoptions in their home country. The next country to be covered is the UK, which was the first to pave the way for liberalization of markets and privatizing the telecommunications sector, followed by Germany and France. Policies of three other countries are covered in detail: Australia; Canada, because of its proximity to the US; and India, because of certain policy elements that have been adopted in the proposed framework. The next part of the discussion is covered by regions – Central America (focusing on Guatemala and El Salvador, because of their use of property rights in assigning spectrum licenses), Central and Eastern Europe, Africa, South and East Asia.

1.2.1 United States

For studying the background information into early radio legislation in the US, between 1912-1934, several sources were consulted [18, 19, 21, 28–30]. The common theme of discussion while evaluating the 1912 Radio Act in these sources was that while the Act exerted central control and oversight in awarding license to radio operators, there was no formal process of license assignment. Licenses were simply awarded by the Secretary of Commerce on a first-come-first-served basis. This worked well for the first few years, but within a decade the popularity of the technology had soared, and consequently the number of radio operators had increased dramatically. As pointed out in the sources, this profusion led to challenges in spectrum assignment, resulting in a need to have a defined policy for management and assignment of spectrum resources – the focus of regulations for the next few decades. The first issue was that there was no dedicated authority to manage the department, which was becoming a challenge because of the sheer number of licenses to manage. Further, as there was no legally available means to decline licenses or restrict usage, there were several lawsuits questioning the power of the Secretary of Commerce in this regard[3]. Finally, there was also confusion on how to treat spectrum resources, and several lawsuits were filed in this regard as well[4].

To counter the difficulties in the enactment of the 1912 Radio Act, the US Congress enacted the Radio Act of 1927 on February 23, 1927. This was in fact a direct consequence from the court cases that, from research [29–32], had steadily eroded the power and authority of the Secretary of Commerce vested by the 1912 Act. The US Congress responded to the confusing provisions by taking over spectrum management and ending the common law property rights in the spectrum in the 1927 Act [32, pg. 83], that had steadily started to permeate as a result of various court discussions, as detailed in the footnotes. This meant that radio spectrum was now in the public domain and private ownership of the spectrum was forbidden. The key provision of the 1927 Act was setting up an independent agency to oversee the radio spectrum licenses and regulate the radio station operating times and power outputs – the Federal Radio Commission, FRC [33].

A key consequence of the 1927 Radio Act was the concept of *public interest* to radio communications, specifically broadcasting. The term, introduced in the 1927 Act and clarified in a 1928 Statement, equated to minimising interference as well as transmitting at regulated scheduled and announced times as well as at pre-fixed frequencies. The interpretations of

[3]There were two cases that showed the flaws of the 1912 Radio Act. The first case was in 1923 (Herbert Hoover vs. Intercity Radio) that arose when Intercity was denied a license renewal citing unavailability of spectrum space. They won the case because the courts ruled that the secretary of commerce has no authority to deny a license and should instead allocate the space causing the least interference [29, pg. 286]. The second case was in 1926 (United States vs. Zenith Corporation) and arose when Zenith Radio, limited to two broadcasts a week, started using other frequencies not specifically allotted to it. When Hoover brought a lawsuit against them, the court ruled against the government pointing out that the 1912 Radio Act did allow radio stations to use other wavelengths (in fact on any frequency in addition to the one assigned) [31, pg. 203-204]

[4]One of the most famous cases in this context came after the Zenith Radio case, between Chicago station WGN owned by the Chicago Tribune and the Oak Leaves Broadcasting station [31, p.g 205-206]. The timing of this case in relation to the Zenith Radio case is important because Oak Leaves, despite having a pre-assigned frequency allotment >50KHz from WGN deliberately started to broadcast on the latter's frequency band causing interference. The reason was because Zenith Radio case showed that under the 1912 Radio Act, there was no authority that could punish the radio stations causing interference to other commercial radio stations. In order to find a solution for this case, Judge Wilson (in absence of any governing statuette) examined other analogous situations and applied common law property rights to spectrum. He invoked a homesteading principle for the spectrum – *priority in time creates a superiority in right*. When applied to spectrum ownership this meant that the first user of a wavelength owned the right to keep using it and courts were obliged to keep competitors from interfering in that frequency band. This case and judge's opinion is said to be the last straw for the government who responded with the 1927 Radio Act and ended all common law property rights in the spectrum landscape [32, pg. 81-82].

public interest are still considered valid in radio communications[5] [29, 32]. Public interest, whether or not directly stated, can be seen as one of the key causes of government's primary role in spectrum assignment in many countries – as seen in later sections.

The 1928 Statement also introduced classes of service based on the sizes and locations of geographic areas served by radio stations – clear channels with higher power usable at greater distances; regional and local channels for smaller geographical areas. This particular concept remained in operation for over six decades [34]. Another consequence of the 1927 Act was that spectrum scarcity was now recognized as a genuine issue. Due to interference, the available spectrum channels were limited and all the demand couldn't be accommodated necessitating methods to address the problem. As engineering solutions could not offer adequate solutions, the FRC was empowered to impose rules and regulations to limit the number of entities actually using the airwaves [35, 36, 33]. The FRC was made permanent in 1930 and its tenure was extended until 1934 when it was replaced by the Federal Communications Commission (FCC) to regulate radio communication and broadcasting industries as well as the wired telecommunications industry [34]. The regulatory structure and policy positions adopted by the FRC however remained mostly in place until 1990s, when auctions were introduced as a means to assign spectrum to operators [9].

The discussion on policy analysis now splits into two areas – mechanisms used for assigning spectrum, and Ronald Coase's argument for market-based spectrum. The former is directly related to the framework, as it reviews the assignment mechanisms used and their advantages/limitations, which will help to formulate the spectrum access methods in the proposed framework. The latter, Coase's argument for spectrum property rights, is important because it is often cited as the basis for moving towards full market-based assignment and justification behind many dynamic spectrum assignment schemes.

1.2.1.1 Mechanisms used to assign spectrum

- Administrative assessments (Beauty Contests): Cave [37] defines beauty contests as procedures where *a body is formed which assesses rival applications, normally using criteria which are well published in advance*. Also known as comparative administrative assessments, this method was used by the FCC to assign licences for over a half century post its formation in 1934. The criteria used by the administrative judge was simply to choose the applicants that would put the spectrum to best use. The licenses were free, except for a normal registration fee. However, the process had several valid criticisms, as summarised in an official FCC working paper that also

[5] They also form part of the issue in developing policies for dynamic spectrum access and cognitive radio.

mentioned that the FCC itself had officially questioned the effectiveness of comparative hearings by 1970s [38]. The key issue cited was that comparative hearing was not an objective process and involved a plethora of lawyers and lobbyists arguing for their clients' plan. More importantly, there was no clear or consistent rationale to spectrum assignment. As mentioned in other similar reviews [39, 40], as soon as the rationale was made clear applicants started to deliberately structure their plans to satisfy the criteria without actually trying to fulfil the promises. As reports mentioned, even when these issues were sorted, the FCC found that there were several applicants that fulfilled the criteria and had to struggle to make distinctions between them often on tenuous and insignificant grounds. The process itself was lengthy and expensive and with three rounds of decision-making it sometimes took more than a decade to assign what was essentially a scarce resource for free.

- Lotteries: Cave [37] defines lottery as *the process in which license is awarded by a draw in which each interested applicant has an equal chance of winning*. Theoretically, this is the fairest means of assigning a resource and was used by the FCC to award licenses in the 1980s. Lotteries were initially proposed as a tie-breaking mechanism in tandem with post comparative hearings, when two or more applicants were equally qualified. Studies reviewing the history of spectrum assignment in the US [37–40] all agree that the issue with using adopting lotteries as the primary mode for assigning spectrum licenses what that the government agreed have a completely hands-off role, except as required by basic technical consideration. In addition, the entry requirements were set very low, which meant almost anyone could participate. This led to tens of thousands of applicants, most of whom were speculators with no intention or capability to construct and operate cellular services. Several schemes to *game* the lottery systems also emerged and remained ahead of measures developed to counter them. The process of adjudicating the disputes was also said to be long and complicated and the regulators soon realised that this new process of spectrum assignment was as flawed, problematic, delay-prone and expensive as the comparative hearings. One of the biggest problem cited by researchers [39, 40] was that the lottery winners were free to resell their licenses, which meant that many of the applicants were merely speculators with no intention of offering cellular services to the public. This, for the first time, brought the cost of spectrum resources into the equation. For instance, Terplan and Morreale [41] discuss the case of Cape Cod cellular licenses, which were brought by a group of partners and resold for $40 million, without building anything. They also cite the NTIA study 1992, which estimated the the market value of licenses given away using lotteries to be between $40-$80 billion. This led to the government factoring in the market value gained by selling the resource, which changed the process and motivations of spectrum assignments drastically.

- Spectrum Auctions: The issues with lotteries and comparative assessments led the regulators to trial another mechanism for spectrum assignment – the auction. Cave [37] defines spectrum auction as *the process in which firms make competing monetary bids for a license granting access to spectrum.* As can be seen, in this form of assignment, the license has a fee which indicates the valuation attached to the resource by an interested bidder. In a fair and efficient spectrum assignment process, license is awarded to the highest bidder, which is the goal of auction design. Auctions can be of many types – closed/open, single-round/multi-round, ascending/descending etc.

  For the 1994 auctions, the FCC considered four of the auction mechanisms as bidding options – the traditional English auction, the Dutch auction, the first price sealed bid auction and the second price (Vickrey) sealed bid auctions [39]. After a rigorous debate, an innovative form of auction was chosen – the simultaneous multiple-round auction (SMRA)[6] – proposed by auction experts Paul Milgrom and Robert Wilson [42]. The auctions proved to be better than the lottery schemes in several ways. First, the money raised by the auctions was unprecedented. Second, unlike the lottery mechanism, the licenses were not awarded willy-nilly. They were awarded to the bidders that valued them the most and who were more apt to make the best use of the spectrum. Third, the time taken to conduct the auction was just five days. Finally, as a bonus, the auction scheme reduced the possibility of successful tacit collision [42].

  SMRA critics have pointed out several issues, especially as the spectrum packaging becomes more complex – vulnerability to gaming such as demand reduction or signalling, and very complex bidding strategy in auctions with multiple lots [43]. In a 1998 paper, Crampton and Schwartz showed that there was some evidence that collusion was used in the initial spectrum auctions, in the first 12 auctions between 1994 and 1998, though it was likely that the parties did not get much benefit out of this [44]. To improve the auction process, several safeguards were introduced, though the basic structure of auctions remained the same for over a decade [43]. The next key stage of improvement from SMRA was the introduction of package bidding in 2008. This is the principle of combinatorial auctions, where bidders can ensure that they either win the package or

[6] SMRA is similar to traditional English auctions except that instead of selling an individual item, a large set of related licenses are auctioned simultaneously (as the name suggests). In each round, bidders can bid on any licenses and the auction closes when there are no new bids on any of the licenses.

nothing at all. The obvious problem with this type of auction is that if a large bidder submits a bid for a package bid for several licenses. Then smaller bidders would find it hard to coordinate their actions even if the sum of their values is higher than the value of the package to the large bidder [45].

To counter the issues with collusion, the FCC has evaluated other mechanisms, the most popular of which are the combinatorial clock auction (CCA) and its variants [43]. A review of the FCC spectrum auctions website shows that to date all spectrum auctions have sed the simultaneous multiple round auction mechanism. However, while the FCC has organized multiple conferences through the years [45] and despite being adopted by several other countries successfully (discussed in sections below), the FCC has not yet adopted the CCA mechanism for spectrum assignment nor has any concrete plans to do so in the near future for the upcoming 5G auctions in the 24 GHz and 28 GHz bands[46].

1.2.1.2 Ronald Coase's proposition of property rights in wireless spectrum

In 1959 Ronald Coase famously questioned the very premise of centralised assignment of spectrum [37]. Coase contended that comparative assessments were an inefficient mechanism to assign spectrum. His work was one of the first that advocated treating spectrum as a scarce resource when deciding a pricing mechanism and choosing a market-based scheme to assign the resource to the operators who believe they would be able to generate the greatest value using the resource [47]. His suggestion was mocked when initially presented[7] and again in 1977 when a commission attempted to reprise the idea[8]. However, it became a reality in 1994, when auctions were introduced in the US to assign ten nationwide narrowband Personal Communications Services (PCS) licences[9].

[7]When he explained the proposal in front of the FCC, it garnered the infamous response *"Tell us, Professor Coase, is this all a big joke?"* [48].

[8]Two other members of the FCC wrote that the chances of using auctions for wireless spectrum rights were equal to the odds of *"the Easter Bunny in the Preakness"* [48].

[9]While the idea of using auctions for assigning spectrum is universally attributed to Ronald Coase, he wasn't the first or the only academic to suggest this method. Noam has pointed out that the idea was first proposed by Leo Herzel in 1951. Herzel proposed that the government could lease the channel for a fixed period to the highest bidder *without making any other judgment of the economic or engineering adequacy of the standards to be used by the applicable*. The only criteria used by the regulator would be revenue maximization as a means to determine the width of channels [49]. This is in fact the strategy currently used by most researchers proposing means for dynamic spectrum access. Other academics to suggest this approach were Arthur De Vany in 1969 and Harvey J Levin in 1971. By mid the 1970s, the idea was firmly planted within the FCC, with their Commissioner Glen O. Robinson cautiously advocating the idea as early as 1976 [48].

In addition to proposing auctions as a method to assign spectrum, Coase also questioned the priority given to government-owned agencies to own chunks of spectrum [47]. For instance, a review of the early US radio regulation from sources [19, 21] showed that if any military or police agency decided that a particular spectrum band was *useful* to them, the 1912 Radio Act had given government rights to prohibit all commercial operations in the band (under the guise of interference), unless the particular agency agreed to cede or share its rights with a commercial entity. Further, the rights allotted to government and commercial entities were different – while a commercial entity could only license the right to use the spectrum for a set period of time, government agencies were exempt from time limits, even if the channel was suitable for commercial purposes. This meant that governmental agencies, by law, were (are) free to hoard spectrum forever based on obsolete technology and that chunks of spectrum could remain off-market, unless there was a decision to lease or share them to other parties.

While Coase's paper and generalisation of the idea are widely regarded within the academia [50], there have been several sceptics questioning his ideas and the justification chosen for proposing market-based mechanisms as a means to assign spectrum (as mentioned above). To be fair, both his original papers were published in the late 1950s when the spectrum regulation landscape was hampered by the lack of independently reliable technical information (also it was still a relatively new area with rapidly changing technical aspects and application scenarios), and in the context of the ad hoc means used by the FCC to allot spectrum.

One of the main justifications given for bringing radio communications under government control was to ensure that best technologies available were used. A case in point was when superior radio systems designed by scientists like Fessenden and DeForest, were held back from active adoption as a result of Marconi's patents [11, pg. 213]. The situation, however, did not change even after the control was taken up by the government. Based on historical events, the usefulness of a band was based on arbitrarily defined *public interest* and any agency was free to not opt for newer technologies if they did not wish to. The most infamous of cases highlighting this issue was that of Prof Edwin Howard Armstrong who developed FM radio that has been covered in studies focusing on early radio regulation and technologies [33, 51]. FM was a superior technology to the existing AM technology. It was capable of dual-channel transmissions and low interference multiplexing. Despite these advantages, private competitors aided and abetted by the FCC ensured that FM did not disrupt the existing technologies, similar to suppression of technologies pre-1912. Additionally, regulation history of the time also indicates that commercial radio stations were favoured over educational and other community radio channels, leading to the closure of many, under the definition of *public interest* [28, 29]. These issues form the core context of the framework proposed in this thesis.

1.2.2 United Kingdom

A review of the early communications regulations history in the UK [15, 52, 53] shows that radio communications regulation has been under central control since its inception. Electric telegraph services, previously provided by private companies, were nationalized in 1870 and radio communications were naturally linked with electronic communication systems. Thus, the General Post Office (GPO) had the monopoly over the electrical telegraph service and soon both the wired and wireless telecommunications systems. The wired telecommunications sector was operated by licensed private telephone companies, with GPO providing the trunk lines. This system changed in 1912 and a public monopoly was created in the telecommunications section. The government had been steadily extending its control over the communications sector[10]. This intent, combined with the aftermath of Titanic-related-events led to the nationalisation of the telecommunications sector in 1912 [15]. Spectrum regulation formally began in 1904 under the Wireless Telegraphy Act of 1904 and was under the Postmaster General. Both transmitters and receivers required licenses[11]. Radio broadcasting remained in the public domain with the BBC being the national broadcaster, though it did see some competition starting in the 1930s from Radio Normandie, a French station and Radio Luxembourg [15, 52].

Despite some minor changes, the underlying radio and telecommunications policies in the UK essentially remained the same until 1984, when British Telecom (BT) was privatised as a result of ongoing policy pushes of the government in the late 1970s. This happened in two steps: first BT was removed from the control of the Post Office in 1981, which effectively ended its monopoly – that began with the expiry of National Telephone Company's (NTC) license in 1912. Second, ways and means of introducing competition into BT were evaluated[12]. BT was finally privatized by selling 51 percent of its shares to private investors [54]. Additionally, the government set out a duopoly policy for seven years, reasoning that

[10]The case of Attorney General v. Edison telephone Company in 1880 was concerned with the issue whether telephone services fell under Postmaster General's purview and was decided in favour of the Postmaster General, cementing the way for future communications regulations to be set up in a similar way [53].

[11]The license fee accumulated was eventually used to fund the British Broadcasting Corporation (BBC) from 1923 onwards [15].

[12]The UK's privatisation programme was unprecedented in that the sale of a company, the size of BT, was on a scale that was never tried before. The regulatory mechanisms put in place to deal with post-privatisation are actually used as a model for other industries.

Mercury Communications needed a chance to get established. After the duopoly period expired in 1991, licensing of multiple service providers was permitted, initially only for domestic services. International communication still remained a duopoly until it was finally ended in 1996 when other operators were allowed to offer international services within the UK [15].

Spectrum was initially assigned in the UK by means of beauty contests, where different firms submitted their licences to a government committee, which then awarded licenses to the candidates that met a set of criteria that was openly published[13]. The first auction in the UK was held in 2000 for five 3G spectrum licenses. The reactions to the auction results have been highly varied. As the auction rules did not permit much strategic bidding, including signalling, the natural strategy of bidding in increments of 5 percent was followed by most operators. The value of the license was also reasonably distributed as most new entrants exited around the same amount and the three identical licenses were sold for almost the same price. The eventual value of licenses were considered to be exorbitant by several observers. The prices raised in this auction set the precedent for spectrum auctions being treated as a source of serious revenue for the government and is one of the reasons governments are reluctant to actively encourage trading or sharing between parties as a means to assign spectrum [55, 56].

The initial auctions used the Simultaneous Multi Round (SMR) format but in 2008 the decision was made to switch to CCA format for the next auctions, which was applied for the first time in 2013 for awarding the 4G licences. The OfCom shifted to SMR for the recent 2.3 GHz and 3.4 GHz auctions, as CCA was thought to be too complex for the auction. In 2010, the OfCom also started to liberalise spectrum ownership by permitting spectrum trading[14]. In tandem with this the ownership period of spectrum bands was extended, at times indefinitely, if there was no other contention from interested parties for these bands. Despite all the efforts and additional changes made to make trading easier, spectrum trading has not been embraced in the UK and the handful of trades that have occurred are a result of corporate expansions rather than trading (as intended) between independent parties [57, 58].

[13]One of the formal requirements was for licensees to adopt the Common Air Interface (CAI) that would allow the handsets to roam between networks and operators. This was later adopted by European Telecommunications Standards Institute (ETSI) as a digital cordless standard [55].

[14]The OfCom has also introduced a Transfer Notification Register (TNR) where anyone could view the license ownership [56].

1.2.3 Germany

Telecommunications in Germany developed as a part of the government communications services, encompassing post, telegraphy and telephone. The government was the sole network operator and was aided by the private equipment industry as the supplier [13]. The focus of communications policy was on homogenisation that would allow the maximum percentage of the population to connect to the existing network. Innovation was discouraged because consumers believed it to be beneficial to be a part of the existing system even if it expands and improves slowly, rather than risk being a part of a radically new system. The policy and attitudes of Germany follows the social market economy concept where market policies are blended with concepts of social group that correct the perceived shortcomings of existing market processes[15]. While the socio-political conditions in East Germany were vastly different from West Germany (prior to reunification), both their telecommunication sectors were centrally controlled[16] [59].

The reform process finally began in Western Germany in the second half of the 1980s, with East Germany following soon after the reunification in the early 1990s. Like other countries, the reform process took place in steps – the first being the separation of the post office from the telecommunications services as well as from the central ministry. Achieving full reform in Germany proved much trickier to achieve than in the UK, even though the push to change was similar and had the same timeline in both countries[17]. The Reform Act was finally passed in 1989 just in time for reunification [59, 60]. The liberalisation process was also different from that followed in the UK. There was no independent regulatory authority and the newly formed Deutsche Telekom retained the monopoly over the network operation and voice telephony services[18] [60].

Because the 1989 Reform Act was the first step towards liberalisation, it was agreed upon that the infrastructure would remain in the hands of the Deutsche Bundespost Telekom (DBP). However, certain fringe areas were now open to competition like satellite, mobile radio and mobile communications. This allowed a second operator to enter the mobile communications

[15]This concept is known as soziale Marktwirtschaft or Rhine capitalism, a third way between laissez-faire economic liberalism and socialist economies. The idea is taken from Ordoliberalism, a German version of social liberalism where the government (or state) has the duty to ensure that the free market potential attains its theoretical potential.

[16]In fact, prior to the 1990s West Germany was often regarded as one of the least open telecommunication sectors in Europe.

[17]This is because of the political structure and landscape in Germany that makes change extremely difficult as it not only has to get approval in the two houses but also pacify minorities, who hold significant veto power over constitutional amendments.

[18]Deutsche Telekom also had the responsibility of subsidising the postal services, adding to the federal budget and modernising the recently reunified East German telecommunications network.

section, leading to Mannesmann Mobilfunk GmbH acquiring GSM 900 license in 1990. The license was awarded via a beauty contest and the winner was selected among 10 candidates. The operators had to commit to several obligatory conditions, if they won the license. Several of these have now become a part of standard obligations when spectrum is assigned to a carrier[19]. This duopoly in German market continued until 1993 when a third license was awarded for GSM 1800 MHz to E-plus. This changed the market from a duopoly to an oligopoly. In 1997, a fourth GSM license was awarded to Viag Intercom. Both these licenses were awarded using beauty contests[20]. The spectrum assignment periods were long-term and the reasoning behind them were not very transparent [61].

The first spectrum auction in Germany was conducted in October 1999 for second generation GSM 1800. The auction participants were the four incumbents. The auction format was simultaneous ascending bid auction. The two winners of the auction were DT Mobil and Mannesmann who secured the spectrum for 10 years[21] [62]. The next auction conducted was the most famous of the spectrum auctions in recent times – the 2000 German UMTS auctions. This auction was also simultaneous, open and ascending[22]. The auction differed from UK auctions in that the frequency bands were pre-packaged with fixed amounts of radio spectrum resulting in fixed number of licenses. In contrast, German authorities broke down the supply of paired spectrum into identical blocks and allowed bidders to aggregate these into variable number of licenses, ranging from 4 to 6 licenses [63]. This is often touted as a positive outcome. Nevertheless, winning the licenses did not actually benefit the new entrants. In fact neither of the new entrant firms – MobilCom, owned by France Telecom and Group 3G with the trade name Quam, and a consortium between Spain's Telefonica's and Finland's Sonera – deployed the UMTS network based on the spectrum they won. In 2002, Group 3G announced that they would go out of business. The next year MobilCom returned its 3G license to the German regulator. This essentially meant that the auctions did not alter the existing cellular market, which continued to be operated by the four incumbent

[19]There are coverage requirements at the end of a certain date, the technology that would be used, anti-competition measures like excluding certain firms from the competition (in the first instance, this was DBP), accepting distribution partners without discrimination, and the payments related to license distribution.

[20]The number of applicants for the license reduced from 10 for the second license to 4 for the third and at the time of awarding the fourth license, Viag was the only applicant. The reduction in the number of applicants is attributed to the requirement of large upfront capital investments that may not payoff in the longer term, as there were already three well-established players in the market.

[21]This auction is often used as an example of how simultaneous ascending bid spectrum auction results in a low-price outcome.

[22]The auction is said to have been more competitive than similar auctions conducted in other European countries and yet was able to raise the highest revenue among them. A total of 6 licenses were awarded – 4 to incumbents and the rest to new entrants.

operators [64]. For the 2010[23]. and the 2015[24] spectrum auctions too, Germany has used the simultaneous multi-round auctions.

1.2.4 France

As soon as the electric telegraph was introduced in France, communication services were placed under a state monopoly. The practice continued when telephony was introduced in 1879. The Posts and Telegraph Ministry was created in 1879 for administration of these areas. The Ministry had allowed licensed operators for a few years but no licenses were renewed in 1889, at which point the ministry took over the private networks and telephony became a publicly supplied monopoly service. The existence of state monopoly meant there was no competition in the market and the growth was extremely slow. Telecommunications was not a priority area for the French government until the later half of the 1960s, brought about by the increasing public discontent with the telephone network. Like Germany, the French telecommunications sector had also been extremely slow to the 1980s liberalisation process. One of the reasons was that the pressure to reform was less because of the development of a reformed and modernised telecommunications network in 1970s that more or less satisfied the demand for advanced communication services in the country [14].

The actual reform process in France started in the mid 1990s. There was support for creation of an independent telecommunications regulatory authority, which was finally established in 1996. During this period, French Telecom wished to create an alliance with the Deutsche Telekom. However, the European Commission refused to approve this without agreement from both French and German governments to liberalise alternative infrastructures rapidly. This was cited as a justification for reform and also for competition in the sector. France Telecom was privatised partially in 1997 although the government remained the majority shareholder [59]. Commercial mobile communications in France began in 1985 when the mobile communication subsidiary of France Telecom, France Telecom Mobiles began offering Radiocom 2000 – a quasi-cellular service linked to Public switched telephone network (PSTN). The first analogue cellular license was awarded to Société Française du Radiotéléphone (SFR) – a privately owned company, thereby introducing competition in the French telecommunications sector (by making it a duopoly) [67].

[23]The 2010 spectrum auction participants consisted only of incumbents. There were no new entrants. The licenses were offered in 800 MHz (digital dividend), 1.8 GHz, 2.0 GHz, and 2.6 GHz [65].

[24]For the 2015-spectrum auction, the licenses were offered in 700 MHz, 900 MHz, 1800 MHz and 1500 MHz. Shortly before the auction, E-Plus (one of the four operators) had merged with Telefonica (the third largest operator.). Hence, there were now three incumbents in the market, who were the only participants of the auctions as no new entrants were admitted [66].

In 1991, both France Telecom Mobiles and SFR obtained a GSM license. A third GSM license was awarded to Bouygues Telecom in 1994. During the duopoly years, the market grew slowly, but awarding the third license increased the mobile adoption rates phenomenally until 2001, though the penetration rate remained below the EU average even during this period. None of the three licenses awarded was through any competitive process. It is also not clear if the government charged a license fee at this point or the price basis of the license fees (if it was charged) [68].

Despite the rising popularity of auctions in other countries France decided to assign 3G UMTS licenses using a beauty contest process. The idea was that the candidates would pay a license fee and the government would choose based on the services they pledge to offer. The government fixed the license prices. The process was not without issues. The application process was started in 2000, and resulted in the government awarding only two of the four available licenses to Orange and SFR [69]. The license process, including the terms and fees, were amended in 2001 and applied retrospectively to Orange and SFR. In this relaunched version of the beauty contest, the license was awarded to the sole bidder Bouygues and the remaining license remained unsold. Thus all the three licenses were given to incumbents. In 2009, the landscape changed a little when Free Mobile was awarded the remaining 4th license, making it the fourth mobile network operator in France. The GSM licenses were subsequently renewed in 2006 for 15 years. The frequency holdings remained the same for all the three players with the understanding that the licenses would be used for UMTS as required [70].

Following the tumultuous UMTS spectrum assignment, France decided to auction 4G licenses. This was done as part of a two-step process – first auction 2.6 GHz in 2011 and then auction 800 MHz in 2012. Both auctions used a sealed-bid combinatorial auction and there were three criteria for awarding the licenses: commitment to develop a regional network and a Mobile virtual network operator (MVNO), and the financial bid . All the four incumbents won the four licenses in the 2.6 GHz spectrum band, while three of them won the licenses for 800 MHz spectrum – Free Mobile was awarded roaming rights in the 800 MHz band [71]. Another auction was held in 2015 for obtaining the license for 700 MHz band. There were six pre-determined spectrum blocks of 5 MHz that were awarded to the four incumbents for 20 years[25] [72].

[25]Orange and Free Mobile won 2 blocks each, while SFR and Bouyges won 1 block each. The auction process used was a multi-round ascending and it took 11 rounds to achieve the final result [72].

1.2.5 Canada

The Canadian telecommunication landscape has been heavily influenced and shaped by the actions of the Bell Company. Alexander Graham Bell introduced the idea of telephone in Ontario in 1874, which led to the formation of the Bell Company in 1880. This was accompanied by the adoption of the 1880 Bell Charter, which gave the company the powers to develop a national telephone network. Bell Company had an unregulated (almost) monopoly in the market until 1893, when Bell's patents expired. The expiration of patents combined with a growing discontent with the Bell Company and its practices led to the independent telephone company movement. These companies were monitored by the municipal governments and were controlled by granting limited and renewable franchises. Despite this, Bell Company's monopoly continued in the Canadian telecommunications sector [17, 73].

Interestingly while the telecommunications industry became more regulated and competitive telephony was successful by all accounts, actions by Bell and several regulatory decisions between 1912 and 1916 actually led to the disappearance of competition from the industry. Because this happened well after telecommunications regulation came into the picture, there has been a strong support of the theory of natural monopoly to explain the phenomenon in the Canadian telecommunications landscape. The reason for this obviously exceptional view is attributed to the technical characteristics of the industry, which ostensibly led to a failure of the natural market. Canada's history of telecommunications regulation is also interesting because of its development in tandem with the Railway regulations –another reason suggested for natural monopoly in the country's telecommunications section [73, 74]. However, the monopoly is not as natural in the market as it is made to seem, as this has not led to one single company controlling the entire telecommunications sector in Canada. In fact, Canadian telecommunications is a piecemeal of seven major regional systems, each of which enjoys a near monopoly within its own territory and is in-turn connected with dozens of much smaller local systems. The fragmented nature of the telecommunications industry hasn't prevented the industry from establishing uniform standards, practices and prices for interconnection. One of the reasons is the willingness of the telecommunication companies to coordinate with each other for commercial interests [75].

Telecommunications regulation remained mostly unchanged until 1976, when the regulation was handed over to the Canadian Radio-Television and Telecommunications Commission (CRTC)[26]. Following this decision, the telecommunications industry in Canada started to move away from the rigid regulatory regime that tied every major decision to Parliamentary

[26]CRTC was set up in 1968 to regulate broadcasting industry and in 1976 its mandate extended to include the regulation of telecommunications companies as well (as they were the common carriers).

approval. CRTC progressively allowed more areas of telecommunications to escape the influence of active government intervention. In terms of regulation, the next move is to embrace Internet as part of its universal service operation, which hasn't been possible, as it is not considered to be an essential service [76].

Radio spectrum assignment in Canada, at the very early stages, resembled the US landscape, though it was much more structured and centrally controlled. Despite the dominance of Marconi's company, the government maintained strict control over the radio licenses. The first Radiotelegraphy Act, developed in the aftermath of the Titanic, was legislated on 6th June 1913, merely reaffirming the central government's absolute control over the use of radio waves. The licensing power was further extended with the addition of specific regulations that included how the applications were presented and their content. The licenses were divided into several classes, including specific licenses set aside for experimental and amateur operations [77]. The status quo was shaken with Leo Herzel's article in Chicago law review [49], but was first limited to theoretical discussions within the academic community. The landscape changed fairly abruptly with the introduction of the cellular phones in early 1980s. As Canada did not have a federally operated communications system, the logical option was a call for licenses, which was issued in 1985. The Canadian Department of Communications continued to use a combination of first-come-first-served and comparative processes to assign spectrum until early 1992 [78].

While the mode of auctions were well known the government was not very enthusiastic to adopt it as a means of assigning spectrum. This changed in 1992 with the elimination of the Department of Communications; the responsibility of spectrum management now shifted to the Department of Industry heralding the acceptance of auctions. However, Canadian telecommunications industry did not support this viewpoint; in 1996 over 95 percent of the industry submissions strongly endorsed the continued use of the comparative selection process. Despite opposition, the first spectrum auction was conducted in 1999 for 40 MHz of PCS frequencies that were held in reserve since 1995 [78].

The auction process continues to face strong criticism, which is probably the reason why not all the spectrum licenses are assigned using auctions. While there is no place where a definitive listing is provided on the processes used for assigning spectrum licenses, a significant number are still assigned using the comparative review process. While licenses awarded using both processes are for a period of 10 years, the difference between the licenses awarded using auctions and comparative review is that the former process comes with a high expectation of renewal whereas the latter comes only with an implicit not an explicit expectation of renewal [79]. In terms of auction mechanisms, Canada has explored multiple formats including sealed bid and simultaneous multi-round auctions, before settling to use the combinatorial clock auctions (CCA) in 2014. The spectrum auctions have also used explicit means to encourage incumbents using means such as set-aside auctions. Regardless of the way to assign spectrum researchers have shown the inefficient usage brought upon due to industry giants muscling into incumbent operations or by spectrum hoarding [80].

1.2.6 Australia

The primary source of information about the history of telecommunications in pre-federation Australia was the Australian Bureau of Statistics (ABS) website [16]. In Australia, telecommunications (in fact all forms of communications in general) has always been considered exclusively as a government responsibility from the earliest days of European settlement. The government was not only responsible for establishing the new communication system, it also held control over the development of the new systems. After the Australian federation was formed in 1901, the Australian Constitution specifically gave the government control over communication systems. At this stage basic level of communication services were regarded as the right of all Australians, irrespective of their geographical locations. As government control was (at the time) believed to be the only way to ensure equitable guarantee of services to everyone, hence federal government retained the power over all communication services including but not limited to postal, telegraphic and telephone services. The control over communication services was given to the Post Master General (PMG) who was specifically appointed for this purpose. However, despite being centrally controlled, the country had no overall communications strategy with patchy coverage, especially in rural and remote areas [16].

The telecommunications landscape changed dramatically in 1905 when Marconi's radio system arrived. Initially, the government wasn't very enthusiastic about this idea because they believed it would harm the existing companies. The additional benefit of providing service to population in rural areas soon brought the idea in favour, and in 1905 the Commonwealth exerted complete control over the wireless medium. Until this time the electromagnetic spectrum was in the public domain, but now it was exclusively the property of the government. This meant anyone (commercial or independent) using spectrum in any way, would need to get permission from the government to do so [81].

Avid interest from private companies made the government realise that spectrum was a very valuable commodity, which in turn led to tighter controls over its usage. The eventual push in the UK to nationalise broadcasting did not prompt the Australian government to do the same. The existing operators amalgamated together to achieve higher efficiency, service standards and economies. The first working system was thus midway between the British system of the on-commercial BBC and the free market practices followed in the USA[27] [82].

The landscape itself experienced a shift from bureaucracy to technocracy in 1975. Also, Australian Telecommunication Commission (Telecom) was exclusively established for all public telecommunication services[28]. The organisation was subsequently corporatised as Telecom Australia and had the dual responsibilities of a technical regulator to all aspects of telecommunications, as well as being the telecommunication carrier of domestic services within Australia – also a monopoly. The underlying reason given for the monopoly was the provision of universal service without considering the cost. The difficulty of providing services to remote areas, which comprises that majority of the geographical terrain of the country, justified this decision. The monopoly ended in 1981 with the launch of the satellite Aussat, which acted as another public carrier system. In May 1989, Australian Telecommunications Authority (AUSTEL) because the first independent telecom-specific regulator responsible for developing quality, safety and other standards – such as inter-operability, equipment and connections to the network, ending the dual role of Telecom Australia [16, 83].

Similar to the UK, the Australian government started to introduce competition in the telecommunications sector by starting with a duopoly. The duopoly was introduced by using a tender process to award the competitor status to Optus, who was licensed to use national facilities and was also allowed to purchase the national satellite service with the purchase of AUSSAT. All other players were refused entry until 1997. This led to the start of the Telstra/Optus duopoly that dominated the Australian telecommunications landscape for the next decade. Optus started to use its own infrastructure from 1993. Vodafone next gained entry into the telecommunications sector in 1992 with an exclusively digital license in 1992 adding a third player in the mobile industry [16, 83].

The Radiocommunications Act 1992 created an independent regulator Spectrum Management Agency (SMA) to manage radio-frequency spectrum[29]. The 1992 Act also introduced

[27] One of the first (though unsuccessful) efforts was the idea of "sealed" radio sets i.e. radios sets that could receive broadcasts from only one station. The stations had the license to broadcast and tied in the listeners by offering them licensed radio that could tune in to only one station. The next idea (after the failure of the sealed licensed sets) was a two tiered system – with A and B licenses. The A licenses were the original sealed licensed format who were dependent on listeners' license fees, while B licenses were dependent on advertising to generate their receives [82].

[28] Overseas Telecommunications Commission (OTC), established in 1946, was still responsible for international communications.

[29] SMA eventually merged with the Australian Telecommunications Authority in 1997 to form the Australian Communications Authority (ACA).

two new licence categories – spectrum and class licences – in addition to the existing apparatus licences category. 1997 was landmark year for the telecommunications sector in Australia – industry was opened up for full competition, Telstra was partially privatised, and spectrum was auctioned for the first time. The provision of universal service obligations also applied to all new telecommunications providers. The first auction used an SMR mechanism which continued to be the auction format until 2013[30]. The PCS-2000 auction for 1800 MHz spectrum licenses is a very interesting case in the Australian wireless telecommunications landscape. This auction actually was the second in the past 2 years to sell spectrum in the 1800 MHz band [84]. The interesting part was that while the 1998-1999 auction raised $158.3 million at $0.14/MHz/pop, the May 2000 auction raised a phenomenon $1.328 billion at $1.26/MHz/pop[31] – the second highest valuation among the world. International pricing benchmarks in 2000 for spectrum in this band were in the $0.23/MHz/pop range [85]. The first auction used an open-outcry format and introduced a new player in the market, One.Tel. Following its initial acquisition, One.Tel wished to acquire more spectrum in the 1800 MHz band to expand its services. The May 2000 auction, in the simultaneous multi-round format, took 138 rounds [84]. Instead of the expected $200 million cost, One.Tel ended up paying $523 million to acquire spectrum in the desired band. The high cost is often attributed to aggressive bidding by the participants [86]. While the Australian Stock Exchange (ASX) raised concerns on the methods used by One.Tel to raise equity to finance the bid, the Australian Communications Authority (ACA) had no issues. One.Tel collapsed within a year of the trade, and a significant part of its collapse is attributed to its inability to finance the high costs of spectrum acquisition [87]. More importantly, the high prices have often been cited as part of shady bidding practices [86].

In 2013, frequencies in 2.5 GHz and 700 MHz bands were assigned using a single auction process and a combinatorial clock auction (CCA) format. Because of the high reserve price, the auction of the 700 MHz band was considered to be a failure. When the residual lots from this frequency band were resold, the format of the auction was again changed to the sequential simple clock auction (SCA). This auction format was also used for subsequent

[30]SMR, and in some cases open-outcry auctions, were used to auction 500 MHz, 1.8 GHz, 800 MHz, 28/31 GHz, 3.4 GHz, 27 GHz, and 2 GHz bands [84]

[31]$/MHz/pop is the standard unit for measuring spectrum prices in the spectrum market. The individual unit $ stands for the unit price of spectrum; MHz stands for the bandwidth of the part of the spectrum to be specified in a spectrum licence in which operation of radiocommunications devices is authorised; and pop stands for the population of the area covered by the spectrum license (in this case population of Australia) [84].

assignment of frequencies cleared up for auction in the 1800 MHz , 2 GHz, 2.3 GHz and 3.4 GHz bands at the end of 2017[32] [16, 84].

1.2.7 India

Like other countries, licensing is a core part of the telecommunications landscape in India. However, as will be seen through the discussion here, the process has been under constant scrutiny, and has almost always been marred with allegations of corruption. The first cellular licenses were awarded in 1992 via a first price sealed-bid process, after the individual bidders were evaluated technically. The rejected bidders soon challenged the license awarding process as unclear and arbitrary. Liberalisation was finally achieved in 1995, by converting the original monopoly to a duopoly for each circle[33] [88]. The next stage was the introduction of the New Telecom Policy (NTP) in 1999[34]. The cellular licenses were made technology neutral in 2003 as part of Unified Access Service License (UASL). The agreement was administratively determined as per the NTP [89].

A discussion on the bundled licensed scheme and the issues it had is presented below. The reason to cover this particular scheme is because, despite universal criticism over its deployment, the original idea has merits and was *theoretically* an ideal combination of public interest and profitability. The discussion is followed by a summary of the auctions conducted post the Supreme court directive to cancel all licenses using bundled license scheme in 2012.

1.2.7.1 Review of bundled license scheme

Table 1.1 shows the key features of the bundled licensing scheme. There were several issues with this scheme. First, the initial spectrum was less than one-third of that made available to major operators in other countries. The rationale given was spectrum scarcity as most of the spectrum was under defence ownership [1, 2]. Additionally, caps on the number of new-entrants was removed leading to a flood of new operators – all on a wait-list to obtain spectrum. To understand the scale, each of the circles had 7-8 operators in 2007. This

[32] Australian Communications and Media Authority (ACMA) does not put any rollout obligations on spectrum licensees. According to the regulatory authority, there is no evidence that rollout requirement encourages hoarding to the extent of inhibiting services. Further, the agency believes that hoarding is not an issue for licenses issued through price-based assignments [84].

[33] For implementing the licensing process, the country was divided into 22 circles, excluding the 4 metro cities. The metro licenses were awarded using a beauty contest, while the circle licenses were awarded using a single stage bidding process. The license fees were revised multiple times [88].

[34] A third government operator was given license (pro-bono) in 1998. Finally a fourth operator was chosen as a result of a three-stage auction in 2001. The licensing period was extended to 20 years (with provision to extend for another 10 years) [88].

number doubled in 2008. This meant that the number of operators reached a point where the government did not have sufficient start-up spectrum to assign to the licensees. In response, the SLC was tightened so that the existing operators were now essentially ineligible for any new spectrum released. The Department of Telecommunications (DoT) did not consider fragmentation, which became an issue with UMTS and LTE later. The micro-management by the government in terms of restricting spectrum assignment based on technology meant that more efficient technology – CDMA – paid the price of being more efficient by deliberately being assigned less resources [1–4].

Key features of the bundled licensing scheme
• License delinked from spectrum • New operators would pay a fixed one-time license fee to become eligible for offering either GSM or CDMA service – License fee is equal to the fee paid by the fourth operator at the 2001 auction – Operators providing dual GSM and CDMA services would pay the fixed fee twice – Annual percentage of revenue is paid as the annual spectrum usage charge proportional to the amount of spectrum licensed. • Operators get a start-up assignment – First-come first-served basis for each license (subject to availability) – 4.4 + 4.4 MHz (paired frequency duplex assignment) in the existing bands (800, 900, 1700 and 1800 MHz) – 2.5 + 2.5 MHz for CDMA technology in the mid 800 MHz band. • The operators could obtain additional spectrum beyond this assignment, if their subscriber base crossed certain threshold – subscriber-linked criterion (SLC)

Table 1.1 Key features of bundled licensing scheme [1–4]

1.2.7.2 Spectrum auctions post 2012

Bundled licensing causes other problems too. The unavailability of spectrum for CDMA, because of lack of sufficient contiguous spectrum, was cited by experts as being against the principle of technology neutrality adopted by the government. DoT also did not consider fragmentation, which soon became an issue with UMTS and LTE. The SLC also came under scrutiny as the focus was on maximising subscribers. This is a unique case where technical efficiency is equated to number of subscribers per base station. Many researchers critique this approach stating that this leads to inefficient use of base stations, which in turn leads to increased demand for spectrum [1, 3]. Additionally, there were economic arguments against the revenue mechanism used. The fixed fee approach – in association with delinked spectrum-license – means that government receives remuneration regardless of whether the operator receives spectrum. Even in case where a licensee does receive some spectrum, the commercial appeal of the quantity is in question. Thus government actions are opposed to the welfare of individual operators [2].

In 2009, the Central Bureau of Investigation (CBI) was directed to look into allegations of corruption on bribery charges between existing operators and the regulators. The licenses granted by this scheme (in 2008) were cancelled by the Supreme Court in 2012 – who mandated that the spectrum could now only be assigned via auctions. Post the Supreme Court's decision in 2012, auctions came to be considered to be a transparent way of managing a public resource. Things however did not change for the better. After cancelling licenses, the 800 MHz and 1800 MHz spectrum were put to auction in late 2012. The high reserve prices set for these meant that there were no takers for 800 MHz and less than half of spectrum in the 1800 MHz was sold. The valuation was subsequently reduced and 900 MHz valuation was doubled. This meant that there were no bidders for 900 MHz and 1800 MHz. Despite reducing the valuation there was only one bidder for 800 MHz, who bid very close to reserve price [1, 89].

The spectrum assignment for 3G and 4G services was done via auction (with standard rollout obligations). When reserve prices for 900 MHz and 1800 MHz were reviewed again for the 2014 auction (set at the average price of various methods analysed), the bids were significantly higher than the reserve prices. A reason was that the previously issued spectrum rights were due to expire and operators needed further access to the spectrum for service continuity. In addition, new entrants in the market-seeking spectrum for LTE created further competition. The spectrum assigned was not contiguous leading to inefficient assignments [1].

India then moved to a unified licensing (UL) regime that required a single license for all services making it a service neutral regime – UL also delinked spectrum from licenses, though migration was not mandatory. All future spectrum would be delinked from licenses. Spectrum trade liberalisation, so that spectrum could be traded in the secondary market, was approved in 2015. All auctioned spectrum was liberalised whereas those that were administratively assigned could be liberalised by paying a related fee. The spectrum liberalisation was technology neutral and the fee was simply the difference between the auction price and administrative fee. Under liberalisation, spectrum can only be sold, not leased. Also block sizes were different for different bands with a 1% fee of market valuation paid to DoT for all trades. Rollout obligations (for the entire spectrum, regardless of the block traded) was to be shared by both the buyer and seller [1].

1.2.8 Central America

During any discussion of spectrum assignment, the two small Central American countries always find a mention – Guatemala and El Salvador. Like most Central and South American countries, Guatemala and El Salvador were dictatorships, underwent multiple military coups and fought with neighbouring regimes several times. The spectrum rights in the countries were directly a result of repeatedly failed attempts at privatising the monopoly operator and the delay in assignment of spectrum. The much touted difference in spectrum assignment in these countries is the rights assigned to the operators for non-public sector spectrum.

1.2.8.1 Guatemala

In 1996, Guatemala changed the spectrum management process from a standard top-down to a bottom-up approach. Because of the poor state of fixed-line infrastructure, all telecommunications in Guatemala is entirely based on cellular communications. There are three providers in the country and intense competition between them is responsible for good service and lower prices for customers. These conditions have allowed the unique *usufruct*[35]-based regime to work very well in the country for a long time. It is regarded as a shining example of Ronald Coase's market-based spectrum assignment idea. The key features of this spectrum assignment mechanism are listed in Table 1.2.

However, following the advent of 4G (and the immense revenues generated by governments around the world through 3G and 4G auctions), the existing usufruct regime no longer seems to be quite so perfect. This is only logical; when Coase suggested market-based assignment for spectrum in 1959, spectrum was not a high-value scarce resource. The similar is true for the Guatemalan case as well. The shambled state of the fixed line communication and low-income status of the country meant that there was an excellent case for free renewals

[35]Defined as *The right to enjoy a property of other, to draw from the same all the profit, utility and advantage which it may produce, provided it be without altering the substance of the thing'. As wireless spectrum cannot be "destroyed or diminished" upon using it, usufruct titles essentially allow rights equivalent to private property rights on spectrum for the time for which the entity holds the title [90].*

- Any private entity can request for unassigned spectrum
- The private entity gains usufruct titles These rights are known as Titulo de Usufructo de Frecuencia (TUFs) and are given to title holders for a limited period – 15 years.
- The titleholder can (on its own discretion) change the usage of spectrum and subdivide or transfer rights to any other entity.
- The titles are subject to only minimal technical limitations – only to prevent interference and follow international agreements to which Guatemala is a signatory.
- The right to choose the technology solely based on a company's own commercial decisions and not be answerable to the government is the key difference between usufruct title and a standard wireless license or authorisation.
- The TUFs can also be used as equity or collateral and the term can be extended for a further 15 years by a simple request – no payment is required.
- The companies have the right to file formal complaint in case of interference from a third party (arbitrated by the regulator). However, the government has been reluctant to enforce these rights.

Table 1.2 Key features of TUFs [5, 6]

of the spectrum rights. However, the government now feels that it risks a loss in millions (that other countries have gained) as a result of auctioning the spectrum rights due to expire soon. It is now mulling the idea of delivering usufruct through an auction or adding a public payment for renewal (sometime in 2019). However, this is not legally possible as under the regime reassignment is possible only when the current titleholder abandons the spectrum [91].

The usufruct regime has also made the government complacent and several other regulatory issues have currently no resolution. For instance, like most countries Guatemala also wishes to change from an analog to a digital regime and all parties (broadcasters and mobile operators looking for digital dividend) are in favour of the idea. However, this would mean (a) moving the broadcasters to a spectrum block suitable to their needs and (b) selling some of the TUFs from the broadcasters to the mobile operators or other spectrum users such that all parties benefit from the transaction. Because of issues like these, Guatemala has not assigned any new spectrum to mobile operators in the last 17 years[36]. As a result, other

[36]Although the government announced a process to assign the AWS band and 700 MHz band has been discussed since 2015, there has been no progress in terms of actual awarding of licenses.

peer countries like Mexico, Dominican Republic, and Honduras have already reformed their spectrum management regime. The next step for the Guatemalan regulator is to reorganise the existing assignments, in addition to making the landscape more suitable for future spectrum auctions for licenses (or TUFs) [91].

1.2.8.2 El Salvador

The 1997 change in telecommunication rights regime in El Salvador was similar in nature to Guatemala. A key aspect of the reform was to remove many of the license restrictions, except interference-related. Unlike Guatemala, the rights are not specifically defined as usufruct in nature; however, licence holders have the flexibility to choose the use of assigned frequencies. Despite the fact that, unlike Guatemala, there is no defined process of resolving interference in El Salvador's telecommunications law, there are little or no illegal interference problems in cellular telephony. This might be because the illegal users were given a stake in the new system with strong incentive to support government protection of their rights [5, 6].

Just like Guatemala, the private property license scheme had issues such as – the guard band separation for interference was a standard number and considered excessive by operators, the auto-extension of licenses without charges, the awarding of licenses based on auctions as the sole mechanism, while also encouraging foreign ownership – the latter two deemed unconstitutional by the Supreme court in 2014 [92].

As there were no further legal issues with auctioning spectrum, Superintendencia General de Electricidad y Telecom (SIGET) agreed to the process. However, the competition regulator objected to the rules of the auction suggesting that it was unfavourable to potential new players – the rules stated that the winners would be decided based on the bidding price, regardless of their current market share or spectrum already owned. The auctions were postponed multiple times. The procedure to assign frequencies and an alternate auction mechanism were approved by the government towards the end of 2016, but the auction has not yet taken place [93, 94].

1.2.9 African nations

Telecommunications liberalisation in Africa started in the late 1990s. However, the success has been extremely patchy because of the volatile political landscape. In fact, only Nigeria and Ghana had managed to successfully auction spectrum. In each of the auctions (for 2.3 GHz and 2.6 GHz in Nigeria in 2013 and 800 MHz in Ghana in 2015), only one operator succeeded to secure spectrum. While there were three bidders for Ghanaian auction, only one company could meet the reserve price. Of the two spectrum auctions in Nigeria, the 2.3GHz auction is the only one where an actual auction was conducted between two bidders. However, the company winning the bid has yet to commence widespread rollout of the service. Many have speculated that this is because Bitflux is not able to secure the necessary investment. The 2.6 GHz auction went the same way as the Ghanaian auction, only one company was able to meet the reserve price and hence *won* 6 of the 14 the available lots. The remaining spectrum remains unsold [95, 96].

The other countries that have tried and failed in their attempts to auction the spectrum are Mozambique, South Africa, Senegal, and Egypt. The Mozambique 800 MHz auction in 2013 failed to attract any bids (apparently due to high perceived reserve price) and was quietly withdrawn. South Africa has attempted setting auctions three times for 2.6GHz, 3.5 GHz and 800 MHz. Each the time the auction was withdrawn[37]. Currently the government has plans to remove all exclusive usage of spectrum and instead have a national wholesale network – there has been widespread turmoil, as none of the players are satisfied with this solution. The Senegal 2015 auction for 700 MHz, 800 MHz, and 1.8 GHz ended in a standoff between the operators and regulators. Again the reason was the high reserve price set for the auction. Finally, Egypt's 2016 auction for 900 MHz and 1.8 GHz faced protests from applicants over high reserve prices and small quantity of spectrum under offer [95, 96].

In all the cases above, as well as in other African nations like Kenya, Rwanda, Tanzania and Uganda, the best solution to date has been a non-competitive assignment process. In these countries, equal blocks/quantities of spectrum are assigned to each operator, similar to some countries in Europe [95, 96]. In addition to this, an additional issue has been the high license fees for 3G. This is a common problem for most of the countries conducting UMTS auctions. However, the effect was felt worse in Africa because 3G spectrum assignments were delayed and now 4G (even 5G) looms ahead making it extremely difficult for companies to recoup their investment [97].

1.2.10 Central and Eastern European nations

Most of the Central and Eastern European (CEE) countries (especially the latter) were governed directly or indirectly under the Communist Party until 1991. Hence, public telecommunications had a low priority and mostly operated on obsolete infrastructure built during or immediately post the Second World War. The networks were either never upgraded

[37] There were several reasons for the serial failures. All of them can actually be brought under a single umbrella – lack of a coherent vision by the government and regulation. The rapidly changing political climate has also added to the chaotic landscape.

or were developed using out-dated equipment. The establishment of the Coordinating Committee for Multilateral Export Controls (CoCom) by the western bloc meant that access to modern technology was forbidden. This meant that there was virtually no competition and hence no incentive for making improvements to the existing infrastructure. Following the collapse of Communism in 1991, the countries opened up their markets quite rapidly [13].

As the task of bringing the existing telecommunications infrastructure to modern standards was immense, several countries opted to offer services by partnering the nationalised companies with their private Western counterparts. Within a decade most countries were able to establish and operate modern digital networks and as a result enjoyed a multi-fold increase in teledensity [13]. Policies of few selected countries from the region – Poland, Hungary, Bulgaria, Albania and Romania – were reviewed, providing interesting insights into policy diffusion and the challenges facing countries with a similar background for developing the framework. Here, we summarise a few key events in the telecommunications policy development history, post liberalisation, chiefly focusing on auction successes/failures. A more detailed review is included in the references.

Poland, a free economy until the Second World War, was one of the very few nations where the telecommunications market was license-based. The country began its efforts to privatise the telecommunications sector in 1991. The market remained a duopoly for the first decade post the privatisation. Mobile communications began as a duopoly till 1997, and a third license was granted (all using beauty contents) in 1997. The first spectrum auctions took place in 2016 for the 800 MHz band. Confusions in policies between the fixed and mobile communications led to a court action against the government by Sferia, initially a fixed line service provider. When the court ruled in favour of Sferia, the decision process was sued by T-Mobile, citing unfair financial practices favouring Sferia. The auction was also used to sell spectrum in the 2.6 GHz band for 4G LTE leading to four winning bidders obtaining the licenses [98–101].

Hungary also began privatising the telecommunications sector in 1990 and by 1995 the majority of the state-owned monopoly passed from the hands of the government. With the acquisition of a 67.3% stake by MagyarCom, Matav's privatisation was at the time the largest in the Central and East European region. Hungary was the first country in the Central and East European region to offer mobile services, in 1990. Spectrum licenses, offered for 15 years using a form of administrative assessment process, converted the mobile communications market into a duopoly. Vodafone entered the market in 1999-2000, when it was granted the license using a tender and an administrative licensing process. 3G licences were also awarded using a competitive tender-based assignment process to two incumbent companies. Licences in Hungary are auto-renewable. An auction was conducted for another license, which was awarded to a state-owned consortium with complete roaming facilities across all incumbent operators. All the current operators challenged this decision in 2012 resulting in an annulment of the results of the auction. The 4G auctions of 2014 were equally nonconventional as the bidders offering the highest price were not necessarily the winners. Accusations of collusion have dogged the winning bidders ever since. Four operators submitted their bids and all four were able to secure spectrum for their operational purposes for a period of 20 years. The bids were assessed using a points-score based on the various components to each bid [102–105].

The Bulgarian telecommunications sector also started the liberalisation process post the collapse of Eastern bloc in 1989. The process started in 1992, though mobile services remained a monopoly until social pressures forced the government to assign rights to create a second parallel operator. The rights were decided by way of an auction that was won by the company Cosmo Bulgaria Mobile. The state-owned monopoly Bulgarian Telecommunications Company (BTC) was privatised in 2004, which then became the third mobile services provider in the country. The two other mobile operators in the country are Max and Bulsatcom. Both primarily provide LTE services in the country. In addition, 4G Com was another operator to secure paired spectrum in 1800 MHz band. Despite being one of the most open sectors, the government has assigned only 28% of the spectrum that has been harmonised at EU level for broadband. Access to the rest is restricted either for military use or for security purposes or a lack of demand, including the popular 700 MHz, 800 MHz, 2.6 GHz bands. A look into the process of assigning spectrum reveals that that first official auction for LTE services, which was intended only for new entrants, actually failed to attract any bids[38]. Hence, spectrum was actually assigned in three blocks using an administrative assignment process i.e. a form of beauty contest, to existing mobile network operators (MNOs). Generally the spectrum is assigned for 10 years and most of this is automatically renewed [106–109].

Post 1990s the Albanian telecommunications landscape was liberalised and in 1992 Albanian Telecom (AMC) was established as an independent organization. The state owned company started commercial operations in 1996 and became the first Albanian mobile operator. AMC started offering mobile services the same year, though until 1999 the services were limited to the capital city Tirana and a few other major areas. The state ownership ended in 2000 when Cosmote acquired 85% stake in the company. The second company to enter the telecom sector was Vodafone Albania in 2002. A third company Eagle Telecom

[38]The reason behind this is attributed to the already high mobile penetration rates in the country (by established incumbents) and high reserve prices.

entered the market in 2004 while the fourth and last company Plus Communications entered the market in 2010. In 2013 ALBtelecom and Eagle Mobile merged and officially became ALBtelecom. Despite the facade of liberalisation, the market is actually oligopolistic. The government started by using sealed bid auctions [110].

Unlike other companies, Romania did not embrace the efforts to liberalise and privatise the telecommunications sector. There was a prejudice against foreign companies when looking for privatisation options, which hindered the efforts. However, the situation changed in 1998 when RT was partly privatised with 35% of the company sold to Greek Telecom (OTE) [111]. Through the 2000s, spectrum licenses were allotted based on comparative assessment (actually on a first-come first-served basis) [112]. The assignment method changed in 2012, when auctions were used for the first time to assign the spectrum licenses. Five companies were approved as participants and 85% of the spectrum offered was sold to the parties. The cause behind the unsold lots has been attributed to flawed auction rules. In this specific case bids in previous rounds were not binding for subsequent rounds, which is thought to be the reason behind unsold lots. Two bidders reduced their demand simultaneously resulting in the aggregate demand becoming less than the aggregate supply. The auction mechanism was a variation of the CCA – first price package clock format. The auction had multiple rounds like the standard CCA auction, however the activity rules were different. The payment mechanism used was the pay-as-you bid, instead of the standard Vickrey-Clarke-Groves (VCG) mechanism. The licenses were granted for 15 years, though there was debate on the ownership period being too long [113].

1.2.11 South and East Asia

As with all other regions of the world, privatisation is seen as one of the key methods of reform and liberalisation in the telecommunications sector in the Asia-Pacific region. Japan was one of the earliest countries in the region (also the world) to start the process of privatisation of the state run telecommunications corporation in the early 1980s, which led to telecommunications market liberalisation. Hong Kong was the other country that had completely privatised the PSTN by 1985[39]. A similar scenario more or less played in some of the key economies in the region – Singapore, Taiwan, Indonesia, Malaysia, Philippines, India[40], Pakistan,

[39]The other two Asia-Pacific countries that managed to complete the liberalisation process of telecommunications sector were Australia in New Zealand in 1992 and 1990 respectively. While South Korea had liberalised part of the sector since 1985, the privatisation of PSTN was only completed in 2002.

[40]Only the international arm Videsh Sanchar Nigam Limited (VSNL).

Bangladesh[41] and Sri Lanka. While competition was introduced, this did not automatically mean complete privatisation of all government held telecommunications companies. For instance, Thailand uses alternative measures like Build-Transfer-Operate, where a private company builds the network and operates it during a pre-decided concession period. After the concession period finishes, the ownership is then transferred to the government[42] [13, 114].

China has not yet privatised its primary PSTN and the competition in the telecom sector is controlled and monitored by the state. The government also prefers BTO arrangements in the telecommunication sector, both for fixed line and mobile networks. Instead of the concession period, the chosen mode of operation is leasing the networks back on either revenue sharing basis or join-venture. Like other countries, the purpose of market liberalisation was to introduce competition. However, the competing companies are other state-controlled entities (instead of true privatisation) [13, 114]. Till 1999, the telecom sector remained tightly controlled without any foreign influence or investment. In 1999, as part of signing the China-US World Trade Organization (WTO) Agreement, China agreed to gradually allow foreign investment in the sector [115]. The wireless spectrum in China is handed out by administrative approval. According to regulatory policies for spectrum in China, the users should pay for occupying spectrum. This can be interpreted commercially in different ways. For instance, cellular mobile companies did not pay anything for the spectrum during the GSM era. Instead, the individual subscribers pay a spectrum occupation fee every year [116]. Following the market opening to globalisation, the government briefly considered auctioning the spectrum. However, the high cost of spectrum during the course of 3G and 4G auctions around the world made the Chinese regulators wary of the practice and the licenses were offered through administrative measures. In December 2016, the regulations were modified to introduce market-based measures like auctions to the spectrum assignment process [117]. There are hopes that auctions might be used to assign 5G licenses (in the second half of 2019 and early 2020), but the government has not yet shown any concrete indications to adopt the process.

Japanese regulatory authorities conducted studies to evaluate spectrum auction as a method of spectrum assignment. Japan, like China, does not use competitive price bidding techniques to assign spectrum. The regulatory authority uses tendering process where operators seeking spectrum allotment submit usage plans that are then evaluated. The allotment period is 5-10 years. In the interim period, the government is free to restructure frequency bands and operators would be required to move. This aspect of the policy was

[41] Only the rural PSTN, Bangladesh Telecommunications Company Limited (BTCL) is still wholly owned by the government.

[42] BTO arrangements are common in Asian economies.

changed post 2012 and now new frequency band users are required to bear migration costs for existing users [118]. In light of the fact that mobile call plans in Japan are more expensive than other countries, the government is keen to introduce competition in the sector. While there are no plans to introduce spectrum auctions as other countries use, the regulator is planning to include some features of this mechanism to assign 5G licenses sometime in 2019 [119].

1.3 Impact of policy diffusion on policy making

1.3.1 Conditions of policy adoption till late 1990s

As mentioned in 1.1.4, the twin foci of the policy review are to understand the conditions under which countries engage in policy adoption and the method of policy diffusion used, along with effectiveness. Figure 1.3 shows a snapshot of the policy changes and the time periods of key changes, condensed for the discussion in section 1.2.

Country/ Region	Authoritarian regulation by 1912	Policy change towards adopting competition in telecommunications		
		Early 1980s	Later 1980s	Early 1990s
US	Y	Y (Lottery)	NA	Y (Auctions)
UK	Y	Y (Liberalization)	NA	Y (Full competition)
Germany	Y	N (State owned)	Y (West Germany - liberalization)	Y (East Germany) + GSM
France	Y	N (State owned)	N (Monopoly)	Y (mid 1990s)
Canada	Y	N (Monopoly)	Y (Wireless licensing)	Y (Auctions)
Australia	Y (indirectly)	Y (End of monopoly)	NA	Y (Spectrum licenses)
Guatemala	NA	N (State owned)	N (State owned)	Y (1996 -TUF)
El Salvador	NA	N (State owned)	N (State owned)	Y (1997 -TUF)
India	NA	N (State owned)	Y (Liberalization)	Y (Spectrum Licenses)
African countries	NA	N (State owned)	N (State owned)	Limited (Mid-late 1990s) – Cote d'Ivoire, Gabon, Ghana, Madagascar, South Africa, Tanzania
Central and Eastern Europe	NA	N (State owned)	N (State owned)	Y (liberalisation early 1990s) – Poland, Hungary, Bulgaria, Albania and Romania
China	NA	N (State owned)	N (State owned)	Y (late 1990s)
Japan	Y	Y (Liberalization)	NA	NA

Fig. 1.3 Snapshot of key time period of policy changes
Y = Yes, N = No, NA = Not Applicable

The figure provides some interesting observations. There were two opposing policy pushes – the push towards increased government control around 1912, and the push towards liberalisation and competition starting in 1980s. From the review in 1.2, it can be said that not all the countries (with telecommunications infrastructure) changed their policies to enforce government regulation in the sector post 1912. The process was gradual, starting in 1890s (in Canada, France and UK) and spreading to the new federation Australia and also the US by 1900s. The year 1912 actually marks the point after which no country had a free-market scenario in the telecommunications sector. The landmark shift in the US policies is, in fact, a clear evidence of policy diffusion brought about by market conditions (effect of competition) and public scrutiny (effect of coercion). As indicated in Figure 1.1, the ensuing policy was sub-optimal.

Similarly, the opposing push towards liberalisation is also gradual, depending on various geopolitical and economic conditions. The period, however, clearly marks the point after which countries that were free and able, started to actively move towards competition in the telecommunications sector. The discussion in this part has been limited to late 1990s (advent of 2G technologies). The effect of new technologies – auctions and new types of ownership structures will be discussed in section 1.3.2.

The push towards telecommunications sector liberalisation started in late 1970s and by 1980s the issue had entered political debate in most countries. The initial push, in late 1970s, was the focus on improving the telecommunications infrastructure in Western European countries (discussed in section 1.2 – for Germany and France). At this point, the US and Canada were the only countries with liberalised economies. The successful liberalisation of the UK was an impetus for Germany and France to follow the path. However, the process was gradual (often in stages) and took place after several rounds discussion with all concerned parties. The liberalisation of the telecommunications sector in Australia and Japan further provided the incentive to Asian and East Asian countries to follow a similar path. In this case however, the path to liberalisation was initially only partially successful, and led to introduction of novel mechanisms like Build-Transfer-Operate (BTO). The process of liberalisation in other regions – Central and Eastern Europe, Africa, Central and South America – started in 1990s. In case of Central and Eastern Europe, the initial push was the fall of the Eastern bloc and subsequent desire to both improve the communications infrastructure and chart a similar path to other countries. This mechanism from Figure 1.1 is an example of learning and to some extent imitation. There was also the added pressure from large private companies, who wished to enter the new markets. The process timeline was also long, and liberalisation has only been achieved in stages. In the case of Central and South America, the fall of the Eastern bloc coincided (approximately) with the fall in totalitarian and dictatorial regimes. The proximity affect and pressure from companies was US-based in this case. The case of Guatemala and El Salvador clearly shows that, while the objective was liberalisation, the policymakers had taken care to adapt the policy development to individual country conditions. This led to successful policy development. The case of Africa is interesting in this setting. An in-depth study of individual country policies was not conducted because of time constraints. However, the research conducted shows that the proximity effect was from multiple regions. Many countries in Asia, the Americas, and Europe had achieved liberalisation by mid-1990s and companies were looking to expand to newer countries. The push to conduct spectrum auctions (discussed in the next chapter) also happened simultaneously, affecting the process timeline. This, combined with economic constraints, have led to only a few countries (6 countries by 1998) to achieve liberalisation.

Figure 1.3 below show the early adopters of liberalisation. Figure 1.5 shows followers in various regions of the world (along with a general overview of reasons to opt for liberalisation)

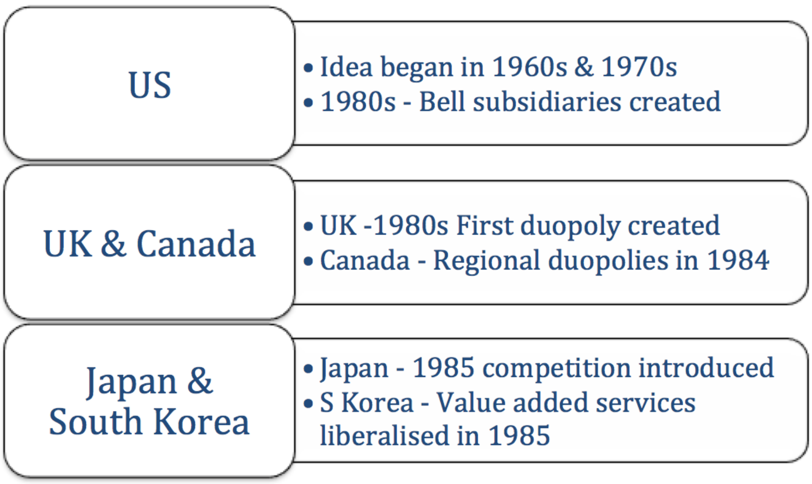

Fig. 1.4 Leaders in telecom liberalisation

1.3.2 Adopting competitive measures to assign spectrum

Competitive measures to assign spectrum, specifically auctions, started in the 1990s as shown in Figure 1.3. The reasons for liberalisation discussed in section 1.2 and summarised in 1.3.1 above, hold true for adoption of spectrum mechanisms as a means to assign spectrum. The other incentive was that governments realised that auctioning spectrum rights was a means to generate significant revenue, following the auctions in the US, the UK, and Germany. This

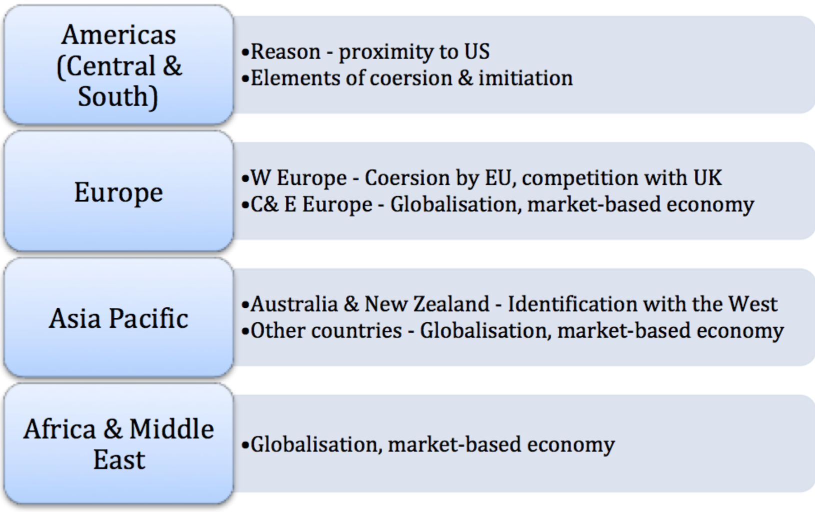

Fig. 1.5 Liberalisation in other regions of the words

attitude is so prevalent that even the countries that have consciously not chosen spectrum auctions (like China, Japan) and countries where previous auctions have failed (several countries in Africa), are actively trying to look into auctions as standard mechanisms to assign spectrum. Recently several countries including China, Japan, Guatemala, El Salvador etc. have changed their legislation to include auctions as valid mechanisms to assign spectrum.

Regardless of the motivation for adopting auctions as a mechanism for assigning spectrum resources, the overall success or failure of the process is dependent on the mechanism used for adoption. Within the telecommunications landscape, most countries have chosen to emulate a selected few in terms of best practices to be followed for regulating and management wireless spectrum. Not unexpectedly, many of these emulated practices have not been successful – as evident in the multiple spectrum auctions that have either failed or have been sub-optimal in terms of expected results. Interestingly, emulating other countries, in the context of adopting spectrum auctions and reserve prices, is not limited to followers in the liberalisation process, depicted in Figure 1.3 and 1.5. Developed or leader countries, from Figure 1.4, have also faced issues when higher revenues generated in auctions, either as a result of high reserve prices (Australia) or new-entrants declaring bankruptcy or merged with existing operator (Germany and UK). In fact, 3G and 4G auctions have generated significantly higher revenues.

Results in *follower* countries, from Figure 1.5, have been worse. For instance spectrum auctions have generally not been successful in any of the African nations, Nigeria being the only nation where auctions have actually been conducted [95]. Central American countries Guatemala and El Salvador subtly altered spectrum rights by ensuring that the owners had usufruct titles to unused public sector spectrum. The rights would still expire in 15 years, similar to most countries, but during this period the private parties enjoyed free use of the spectrum assigned, which could be leased, sold or subdivided at will. The management scheme is essentially deemed as a successful example of Ronald Coase's proposed ideas in the1960s [47], though experts suggest that its success is because the possibility of interference is extremely low [37]. Several other countries have challenges, clearly showing that there are other factors at work.

A review of the spectrum auctions showed that many 3G and 4G auction raised significantly higher revenues [120]. The significantly higher revenues generated, contrary to initial expectations caused many issues. Many new entrants went bankrupt (for e.g. Germany), Incumbents are still trying to recoup the costs (the US, India, and the UK). This, in turn, affected the willingness to participate in future auctions, delaying deployment of newer generation technologies, at least in developing nations (especially countries in Africa). Thus, it can be concluded that the government's focus on revenues adversely affects the market value set on the spectrum. Many auction failures have been attributed to high reserve prices (e.g. India, Australia), leading to unused resources. In fact, the actual spectrum price assignment procedure is not market-based at this stage, because the government is an interested party (seeking high revenues) and is responsible to set the floor prices. While it is true that as a scarce resource, spectrum should ideally command high access prices, it is also connected to *public good*. The uniqueness of the resource lies in the fact that services using wireless technologies are increasingly considered to be necessary services. The other concern is that, reserve prices set are often ad-hoc. Governments have been known set reserve prices based on either imitating other countries (which has proven to be not optimal in case of Australia) or based on obsolete information (case of Indian reserve prices and SLC determination)

Based on this information, one of the core postulates of the thesis is that active government intervention in the spectrum landscape is detrimental to the efficient assignment of spectrum (even if it is based on market-based mechanisms). A key recommendation from the review is that governments should actively look into policy diffusion, as a means to check whether spectrum assignment does not use imitative, excessively competitive or coercive forces to formulate policy objectives.

1.4 Role of the government

The exploratory review of policy history in section 1.2 and 1.3 has also shown an issue with the way spectrum auctions are conducted. The auctioneer – the government in case of spectrum auctions – is not similar to a standard auctioneer (or seller). Even as a seller of resources, the government has multiple objectives. The Radio Spectrum Policy Group (RSPG) has listed multiple common objectives [121], including but not limited to:

- Efficient spectrum assignment – given to the highest bidder based on a pre-determined fixed reserve price or to multiple buyers on a pre-determined fixed price
- Ensuring all available spectrum is assigned for use
- Introducing/promoting & encouraging/enhancing competition – by means of spectrum floor caps, set-asides, caps/limits on acquisition or determining lot sizes and types (generic or fixed lots) etc.
- Improving coverage in rural areas
- Providing new business opportunities, employment and promoting innovation and adoption of new technologies

The objectives discussed above have been distilled by RSPG from the policy objectives of the European Union (EU) Member States. Reviewing the policies of other countries (listed in Table 1.3) shows that policy objectives are mostly similar for countries beyond the EU as well. Interestingly, while elements like "maximizing public benefit", "flexible usage", "efficient/competitive assignment", "setting up transparent/competitive/unbiased license costing schemes" – all find their way in some form in all the policy objectives, none of the objectives specifically relate to maximising the costs generated from the sale of licenses. This is actually extremely incongruous given that most countries have either already opted for (or have attempted in the past) or are in the process of moving towards an auction-based assignment scheme for spectrum assignment. This undertaking is usually combined with setting up a pre-decided reserve price and has the objective to generate the highest revenue yields from selling spectrum to commercial operators.

In countries where auction is the chosen mechanism for the sale of spectrum licenses, the inability of one or more (sometimes all) commercial MNOs to reach reserve price means that the spectrum simply remains unsold. Economic researchers into spectrum auctions generally consider the process to be successful if the revenues are maximised [122, 123]. The notion of *public good* puts constraints on the revenue maximization by the government. This leads to several anomalies, in terms of what should be expected from the government, as discussed below:

- Despite indicating otherwise in policy documents, the success of competitive spectrum assignment is decided based on the revenues generated. These are clearly indicated as expected inputs for the Treasury, generated from sale of a public resource[43] [46, 84].

- Curiously, while auctions where no spectrum has been sold are deemed unsuccessful and auctions with a few unsold spectrum lots are deemed sub-optimal, the unused lots are not registered as a *loss*. This is an incorrect assessment because spectrum is unlike other resources in that it can't be stored and it is wasted every instant it is not used. There was no official document/study expressing the loss of revenue as a result of unsold spectrum [46, 84].

- The success of license assignment using price as a mechanism to assign spectrum is not a guaranteed outcome despite the much-touted monetary receipts. The impact of unsuccessful auctions on competitors is discussed in section1.3.2. The actual loss is to the public, in the form of delayed or non-existent services.

- Research also shows that introducing secondary trading cannot offset the effect of imperfect assignments. This was already known when lotteries were resold (discussed in section 1.2).

- The cases of Guatemala and El Salvador show that rights assignment, even when they are desirable, must still allow for flexibility due to the rapidly changing spectrum landscape.

The key issue here is that none of the governments have indicated that reaching target revenue is a crucial part of the auction process and that if the bidders are not able to reach the reserve price there is no recourse except to make the spectrum lots inaccessible for any use for a few years. As spectrum generates revenue for the government as a valuable and scarce resource, unused spectrum is a loss a government should be always keen to avoid. At the same time, reducing reserve price is not an option because this would give bidders a motivation to collude with other parties to drive the price down, leading to anti-competitive practises (most recently seen in India, discussed in section 1.2).

[43] Governments have insisted that their motivations for assigning spectrum are not revenue related, even though it is not true. Many researchers have commented that the license rents for public treasury is a more efficient way as compared to funds generated by use of taxes. The latter has been demonstrated to cause tax-distorting social losses – in the form of deadweight loss.

1.5 Summary of Chapter 1

In this chapter a review of policy development history in multiple regions of the world was presented. The purpose of the review was twofold. The first was to understand the requirements of the framework. An exhaustive look into the policy building process of multiple countries indicates a clear trend towards adopting workable, and more recently, revenue generating policies. The impact of policy diffusion provided the insight that the structure of telecommunications sector – characterised by the prevalence of large companies and a history influential international governing body International Telecommunications Union (ITU) – all but ensures that the telecommunications policies should be built around similar frameworks. This means that policy diffusion in the sector is not only inevitable but also necessary. However, individual governments must consider local conditions to ensure that emulated policies are adapted suitably. This also indicates a need for a common framework that can be used to *efficiently* assign the right to use spectrum. The second purpose was to understand the role of the government in policy building. Proposals for market-based frameworks use the generic word *auctioneer* [122, 123] and the term interchangeably represents all sellers. The involvement of government agencies in the trade would logically shift the power balance and skew the economics of the trade (Asian countries like India, Bangladesh, and CEE countries like Bulgaria, Albania). However, unfettered competition without oversight is also an issue given that many of the telecommunication companies are big multinational corporations with a sprawling network infrastructure portfolio, built over many years. This skews the market against new entrants and hampers the development of new technology. Hence, in addition to flexibility, the framework requires a regulator who is able to intervene as required but only provides an arms-length oversight. In Chapter 2, other requirements of the framework will be discussed that will help in building the skeleton framework.

Chapter 2

Building a framework for spectrum trading

This chapter introduces the proposed framework for spectrum assignment and its features. The discussion starts with a justification for the need for such a framework and the key features expected from a new framework. The framework is then presented along with the mode of adoption in stages. Key parts of the framework are presented, followed by a discussion on how the proposed model is similar to others proposed in the literature. The chapter ends with a discussion on spectrum-infrastructure dynamic and how its applies to the proposed framework.

2.1 Need for a new framework

Results from a policy diffusion based theoretical review of telecommunications policies of several countries conducted in Chapter 1 showed a high prevalence of imitation for adopting policies with mixed results. Chapter 1 also showed issues with the multiples role of government in the spectrum assignment process. This, by itself, is not a valid reason for the development of a new framework. Simply put, the purpose of the framework is to ensure more competition in the sector, which means effectively reducing barriers of entry so that small players can operate in the market.

There are multiple factors that make the current mode of spectrum assignments untenable. These are discussed in this section. First, the issues with a command-and-control regime are presented in Section 2.1, which goes beyond the issue of multiple hats worn by the government. Command-and-control access has often led to companies acquiring spectrum over the long-term. Hence, command-and-control and long-term access are often used interchangeably giving the impression that they mean the same thing. A review of the studies focusing on newer mechanisms for spectrum assignment, surveyed in [124, 125], show that the models discuss only short-term access, which strengthens this impression. However, command-and-control and long-term access are not the same. Section 2.1.2 discusses the trends towards long-term spectrum ownership and the reasons behind the trend. Governments have employed measures to induce competition in markets and encourage smaller players. Section 2.1.3 discusses the effectiveness of these measures. Discussion in Section 2.1.4 summarises the reasons for a new framework and the features of such a framework.

2.1.1 Issues with the command-and-control regime

As a participant (seller) in a market transaction, the focus is on getting the highest revenues from the trade. As another type of participant (buyer), the focus is on getting the resource at the lowest price or with maximum concessions. As a regulator, the focus is on ensuring that the trading process is fair and no buyer has unfair advantage. As the government, the focus is on ensuring that the resources are assignedd efficiently, resulting the maximum *public good*. Often in the spectrum marketplace these roles have clashed, resulting in inefficient assignment processes. The bigger issue is the lack of transparency. For instance, there is no clear indication on how reserve prices are set in a country for a particular auction nor the point at which spectrum auction is concluded as a failure. There are reports from consulting firms that have been used by governments to conduct auctions, like Plum Consulting [85], Analysys Mason [109], and NERA consulting [43], describing how to set the reserve price.

Similar information is available on some government websites [6, 84, 46] explaining the process, but the method used for arriving at the exact figure is not explicitly stated. Similarly, while government websites show the results of auctions, there is no analysis or review of what is essentially the sale of a valuable resource. From this it can be concluded that the process of spectrum assignment needs more transparency and less active interference from the government. A general discussion on regulations and the philosophy of planning usage around changing technology is discussed in [126].

As discussed in Chapter 1, central governments' control over the landscape extends to spectrum band usage harmonisation. Interestingly the usage is collectively decided and legislated on the basis of what band is available in the countries suitable for the existing technology without any consideration of flexibility. This seems extremely short-sighted in light of the drastic changes in the technology in this area. The inflexible and central regulation approach has worked in the past because newer technologies merely meant bringing higher (or lower) frequencies under regulation. However, with existing communication technologies now reaching the TeraHertz and even the visible light frequencies, there are not any empty frequency bands left for legislation. In addition to this, technical advancements have made it possible for different cellular technologies and applications to co-exist together – meaning that sharp segregation of frequency bands based on technology is an obsolete policy objective.

assignment

Several reports have projected explosive growth in data demand and machine-to-machine (M2M) traffic in the next decade and beyond. According to the 2017 Cisco Mobile Visual Networking Index Forecast, mobile traffic would increase by 7 times between 2017 and 2021 and will account for 20% of all IP traffic by 2022 (up from 9 % in 2017) [127]. The ITU report corroborates this information and further predicts that Mobile traffic would increase at an annual rate of 55% between 2020 and 2030 – excluding the M2M traffic. In 2015, the spectrum demand for International Mobile Telecommunications (IMT) services in the three designated telecom regions of the world was 1300 MHz. However the C&C structure of the telecom landscape has ensured that in all the three IMT regions almost 1000 MHz spectrum is potentially available, but has not been licensed [128].

Spectrum cannot be stored, so the resource is wasted every instant it is not used. The gap between available spectrum and the demand for spectrum is mostly due to administrative reasons. Studies conducted on behalf of the ITU [128, 129] show that a large part of the spectrum in South and East Asia, Africa and South America has not been assignedd because it is under the control of defence and policies on how to make this spectrum available have either not been developed or were not yet clear. This creates an artificial scarcity of spectrum often leading to incorrect pricing [129]. In addition to this, another reason for non-assignment that is common to all regions is the setting of the appropriate licensing fees and the most competitive method to assign spectrum so that it generates the maximum welfare. In countries where auction is the chosen method for spectrum assignment, the reserve prices have been set so high that competitors have chosen not to participate in the auction. Even when parties have managed to participate in the auction, the financial burden because of the high costs has meant that the roll out of the network has been delayed[1] [129]. Countries traditionally using an administrative approach to assign licenses have been accused of suppressing growth and competition. The government in these countries (China, Japan etc.) have increasingly shown an inclination to adopt auction mechanism (discussed in Chapter 1), thought their wariness is understandable. Regulators in some countries like the UK, the US, Canada, Australia and Europe also seem to be aware of the inflexibility of the current assignment framework as evidenced by the reports commissioned for flexible assignment mechanisms [6, 7, 121, 130, 131]. These reports have led to the introduction of newer spectrum assignment schemes, reviewed in Section 2.3.4.

2.1.2 Long-term access still preferred

The wastage of spectrum and the economic objectives of the government would suggest that long-term exclusive access of spectrum should be at an end. Surprisingly, as shown by the discussion and survey below, the opposite is true. Here, a short summary of the information concerning current licensing periods for the countries covered as part of survey (as discussed in Chapter 1) is presented.

In 2005, the UK government became the first in the world to introduce the idea of licenses for an indefinite period[2] [132]. The licenses would be offered for a fixed minimum period, after which they can be auto-renewed. The government retains the right to revoke the licenses under extenuating circumstances, mostly related to spectrum management – only after the initial license term is over and after giving a five year notice. The shift has attracted little opposition, showing that businesses are not entirely opposed to the change. In fact, in the US the FCC has adopted a similar process for spectrum licenses [133] – albeit it is administered somewhat differently. Instead of giving the licenses indefinitely to the licensees and having them pay annual fees, the regulator insists on periodic renewal of their existing licenses after retaining the licenses for a fixed initial period. The renewal is almost guaranteed unless it

[1]Many African nations are a classic example of this issue.

[2]At this point, this was only for spectrum licenses in Ireland and Northern Ireland

violates similar conditions as in the UK – discontinued use for a long period, reduced quality of services etc.

Because of the political turmoil, several countries in Central and Eastern Europe such as Poland, Hungary, Bulgaria etc. prefer auto-extension of existing licenses [101, 105, 109]. The reason behind the auto-renewal policy of spectrum licenses in Nigeria and South Africa [96] is similar. Auto-renewal of spectrum licenses is slowly gaining acceptance in mainland European countries too. Countries like Italy, France and Finland have provisions for renewing the licenses one time, which takes them to the next decade [134]. Similar policies of one-time renewal of licenses have been adopted in Brazil and Bangladesh [135]. The trend is the same for countries where the licenses are renewed using auctions. While there is no provision for auto-renewal the license period has been extended to 20 years and more in countries like Ireland (27 years) [132], Austria (21 years for 900 and 1800 MHz) [134], Canada, New Zealand and Australia (20 years) [6, 84]. Singapore and Hong Kong don't follow auto-renewals but the existing MNOs have the first right of refusal for part of the spectrum that is auctioned, to allow for continuity of services [128]. Countries like Japan and China have a wait and watch attitude and as their spectrum is administratively assignedd [117, 119], there are greater chances for existing companies to retain their licenses for a longer term, if they have shown themselves to be competent and popular with the consumers.

Additionally, the data gathered from the references (cited above and in Chapter 1) was used to determine the number of mobile network operators (MNOs) in these countries. The results are depicted in Figure 2.1. As can be seen most countries have between 3 and 5 major MNOs. This can be taken as the optimal range for the number of major mobile infrastructure operators. A few countries with large areas like the US, Canada, Russia and India the total number of operational MNOs exceeds the optimal range, however, the number of nationally operating major MNOs still falls within the range. [3]. However, out of these only 4 are major national operators with mobile network infrastructure built over a significant part of the country. The rest are regional operators whose operations tend to be limited to one or two regional areas.

This shows that central intervention is required to reduce entry barriers and encourage competition within the industry. At the same time, spectrum – especially in a few bands – is

[3]This would have been true for China as well. But the political structure within the country has ensured that operations are limited to 3 government companies. Other countries occupying large areas are Canada and Australia. Canada fits into our model and has 4 major operators (and a handful of minor operators) while Australia has 3. Australia's lack of minor operators can be attributed to the fact that a major chunk of the country is inhospitable and the population is limited to merely the coastal regions.

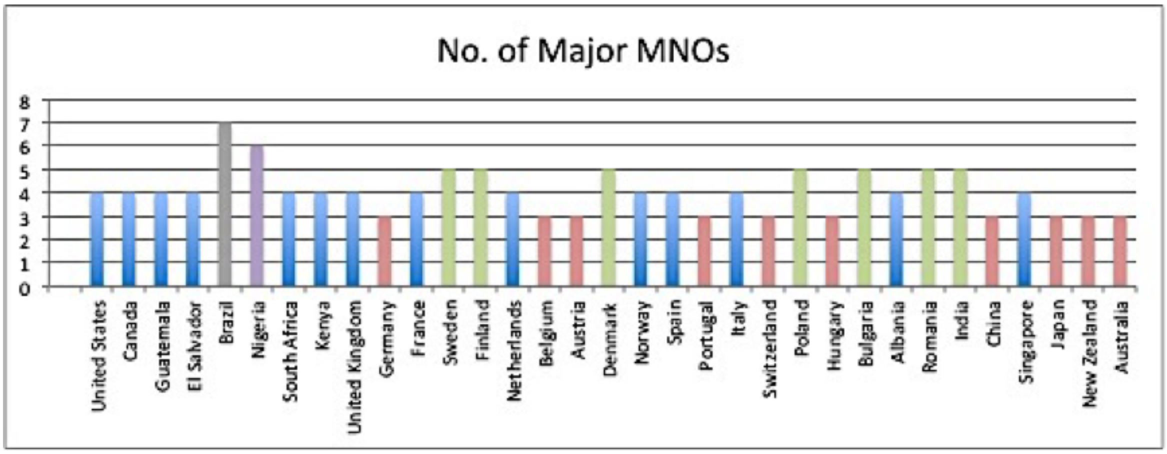

Fig. 2.1 No. of Major MNOs in each country

a valuable as well as a scarce commodity. Effective utilisation of this resource is essential to achieving economic benefits as well as public welfare.

2.1.3 Review of in-auction safeguards

When 3G mobile services were introduced, several governments took additional initiatives to further reduce the entry barriers and encourage competition. None of these have been particularly successful.

1. Spectrum set asides – One of the ways adopted to increase competition in the telecom sector is to set aside certain spectrum blocks for new entrants [135]. This measure was adopted in the Canadian 2008 auction for advanced wireless services (AWS), where 40 MHz of 90 MHz was set-aside for new entrants. The consequence was that both the set-aside and unrestricted spectrum was sold at distorted prices[4]. Further, the market share of the incumbent national MNOs was barely affected by this measure. In the UK, the set-aside measure was deployed in the 2000 3G auctions by reserving one of the 5 licenses – one large license out of 2 large and 3 smaller licenses – for a new entrant. A review of the auction discussed in [64] shows that the revenue from the set-aside license was less as compared to what it would have been if there was no set-aside. In addition the new entrant struggled for over a decade before making any profit. Finally, two of the market participants merged in 2010, meaning that the number of competitors remained the same as was before the auction. This shows that spectrum set-asides are an effective strategy to promote competition in the wireless telecom sector.

[4]The spectrum was sold at 3 times the prices for similar bands in the US and failed to attract national entrants [135].

2. Spectrum caps and floors – Another way used to increase competition in the mobile communication sector is to fix spectrum caps, sometimes along with spectrum floors. As the name suggests, caps are the upper limit of spectrum that can be won by each individual operator, while floors are inverse of caps where an operator is guaranteed a minimum viable portfolio, if they are able to pay the reserve price. Caps and floors[5] are the most common measures used to avoid monopolies and bankruptcies [135].

   Explicit spectrum caps and floors were used in the German 3G auction in 2000 as discussed in studies reviewing the auction in [63, 64]. There was a minimum and maximum bid for participants. Each winner was able to secure the minimum amount of spectrum and there were two successful new entrants. The auction raised the highest revenue at the time and was considered to be immensely successful, raising the expectations of governments from such auctions. However, neither of the 2 new entrants was able to deploy networks using the spectrum they won and both failed to survive in the market[6]. The Austrian 3G auction reviewed in [64, 134, 55], shows that the auction was styled on the lines of the German auction yet is considered as a spectacular failure. The revenue generated was one-sixth of that generated in the UK and Germany. More importantly, despite the measures adopted, the auction failed to increase the number of competitors. Only one of the new entrants remained in the market, the other having sold its license to 2 of the incumbents. In fact by 2012, the number of competitors in the industry had reduced to 3 as a result of mergers and acquisitions. The Indian 2G spectrum debacle has been extensively discussed in this context in the Chapter 1. The administrative assignment used a form of spectrum floor – assigning fixed spectrum to all those who requested it – but was entirely unsuccessful [1–4]. This shows that spectrum caps are an inefficient way to assign spectrum even in administrative assignment regime.

3. Bidding credits – This type of advantage refers to a price discount offered to preferred bidders, usually new entrants, over any bids that they make[7] [135]. This measure was adopted by the UK government in 2013 to increase the number of competitors in the

[5] Spectrum floors, in the form of spectrum blocks, are in fact the norm for spectrum auctions and almost all spectrum auctions use this means to offer chunks of spectrum.

[6] 3G went out of business and Mobilcom returned its license back to the German regulator [64].

[7] Sometimes credit is offered when an MNO agrees to host a competitor MNO over its network or provides roaming facilities etc. However, in such cases the price benefit is balanced by the services offered and does not distort the true valuation of the resource.

industry[8]. However, within 2 years the new entrant had acquired one of the incumbents, leading to the number of competitors remaining the same [136].

Interestingly all the above three methods of promoting competition had already been proven (according to [44, 64, 137, 138]) to cause distortion in auctions as far back as the first spectrum auction in the US i.e. the 1996 auctions for PCS licenses. Several new companies had entered the market during this period due to measures adopted by the government to reduce entry barriers for new entrants. Of the new entrants MetroPCS, NextWave and Urban Communicators PCS were unable to meet even the generous financing terms and filed for bankruptcy[9] and lost their licenses. Several other companies receiving bidding credits and preferential financing terms also struggled to retain the licenses [64].

It can be concluded that while it may be beneficial to provide lenient or preferential terms to promote competition in the mobile telecom sector, interference in assignment/auctions – whether using spectrum caps, floors, set-asides or bidding credits – only distorts the valuation of the spectrum and does not lead to increased competition in the sector. In most of these cases a significant chunk of spectrum was left unused as a result of bankruptcy or disputes – a wasted resource. In a fact according to a study [138], discriminatory rules in the 1996 spectrum auctions have led to a $70 billion loss in consumer welfare.

2.1.4 Reasons for a new framework

From the discussion in Chapter 1 and Section 2.1.1, it can be seen that currently, spectrum is offered only periodically for public or commercial access. ITU's study [128] has reported that a significant proportion of the spectrum bands in the 400-3400 MHz frequency bands are reserved for defence usage in several countries of the world. The report further points out that even in EU regions, where the spectrum access is at the highest levels, not all the available spectrum is licensed. This is because auctions or other means for allowing spectrum access are only conducted periodically and there are sometimes years of waiting period before assignment. A part of the reasons for wait period are genuine issues like ongoing

[8]Hutchison was offered an 18% discount to acquire spectrum, but in 2015 it moved to acquire O2 and the number of competitors in the UK mobile telecom industry reverted back to 3 [136].

[9]MetroPCS and NextWave participated in the set-asides bands for the broadband PCS license auctions. They also participated in FCC's instalment financing scheme (in addition, MetroPCS received bidding credits) but defaulted on payments. Urban Communications PCS participated in the auctions for unreserved bands for the broadband PCS license and participated in FCC's instalment financing scheme.

refarming[10] – for instance the spectrum bands that require switchover from analogue to digital broadcasting.

However, based on the review of policy landscape of countries conducted in this work, a sizeable chunk remains unoccupied because of the following reasons:

- Occupied by defence with no clear plan to open up the spectrum bands under control.
- Legal disputes between government and commercial parties regarding ownership.
- Spectrum licenses returned due to bankruptcy of one or more commercial parties.
- Long auction set up times.
- Long wait times before the infrastructure for a new technology is set up

The study into white spaces in spectrum and dynamic access is a significant theme in academic research. However, there is a divide between the research and its adoption into the communications sector. This can be attributed to the following reasons:

- Lack of a comprehensive framework that would suit multiple parties – similar to a common electricity trading framework, covering all scenarios of operation.
- Understandable apprehension in moving the model away from a system that has worked for nearly a century without change.
- Lack of the path of progression from current long-term contract to a real-time dynamic trading scheme.
- The dynamic trading scheme does not take into account the infrastructure costs and the cost of R&D.
- There are no provisions for regulatory oversight. Some oversight is necessary considering that the resource is scarce to the extent that spectrum-crunch is a valid basis for multiple research proposals such as [139, 140] and those surveyed in [141].

[10] Spectrum refarming refers to changing the use of frequency bands. Some of these changes, like transfer from broadcast to broadband, are quite contentious and hence take a long time to be approved. Regardless of the reasons for the change, the process of refarming requires regulatory intervention and is generally a very lengthy and expensive undertaking.

- The models that encourage shifting from long-term (auction-based) trading to a real-time dynamic are dependent on maximising revenues and minimising fragmentation, despite the fact that the primary purpose of a dynamic trading scheme is maximising spectrum utility [124, 125]. While difficult to ascertain, the goal should be revenue generated per unit time, which in turn would be a direct function of spectrum utility.

2.2 Proposed change structure

Much of the research in this area has focused on bilateral trading between two parties as a solution to bureaucratic delays. A review of surveys collating information from several such research studies [141, 124, 125, 142] shows similar solutions suggesting that this may be the future of spectrum assignment. However, as the landscape moves towards bilateral trading and away from the traditional centralised pool-based long-term contract structure, it is logical to expect that future frameworks will be inclusive of multiple trading/sharing formats. In addition, the future spectrum assignment process should include flexibility in time frames. As spectrum availability is limited in time-space, allowing multiple trading/sharing formats will stimulate greater spectrum utility – which is the purpose of all dynamic-spectrum trading schemes, regardless of their approach to trading spectrum between parties.

For this reason, a staged process for adopting dynamic spectrum access is proposed in this thesis. Cases of liberalisation, presented in Chapter 1, showed that regardless of the country and its political structure, the changes in the telecommunications sector from government monopoly ownership to a corporate and partially commercial structure was achieved in stages. It is also a reasonable expectation that commercial parties and other incumbents would also prefer a progressive opening. The acceptance by incumbents remains one of the main barriers to the opening of telecommunications landscape to autonomous artificially intelligent nodes such as cognitive radio. Governments, in fact, have been an early adopter of the idea of commercial operators sharing the erstwhile-restricted parts of the spectrum[11].

The staggered opening of the regulatory landscape is used as the backdrop for demonstrating our dynamic spectrum-trading framework, which is called the Bring Your Own Spectrum (BYOS). The BYOS framework is a method to bring in the "as-a-service (aaS)" model in the spectrum assignment landscape either in the form of Spectrum as a Service (Saas) or using a

[11] Case in point is the military operator (EU) and coast guard (UK) opening access to their spectrum for shared access under the ASA/LSA licensing schemes. Another example is the ISM band, which is used by xG technologies in the US to offer commercial cognitive radio services. While all the third party trading is freely allowed, it has yet to be used in any country

combination of spectrum and infrastructure to offer Capacity/Data as a service (CaaS/DaaS) to the end users. Key stages of the change process are presented below.

2.2.1 Stage 0

The **Stage 0** is a representation of the current spectrum landscape. Figure 2.2 represents the main players and the interactions between them. The current landscape can be notionally represented as a centralised pool-based long-term contract structure between two parties, though parts of the spectrum have been reserved for amateur or free-shared access by multiple parties.

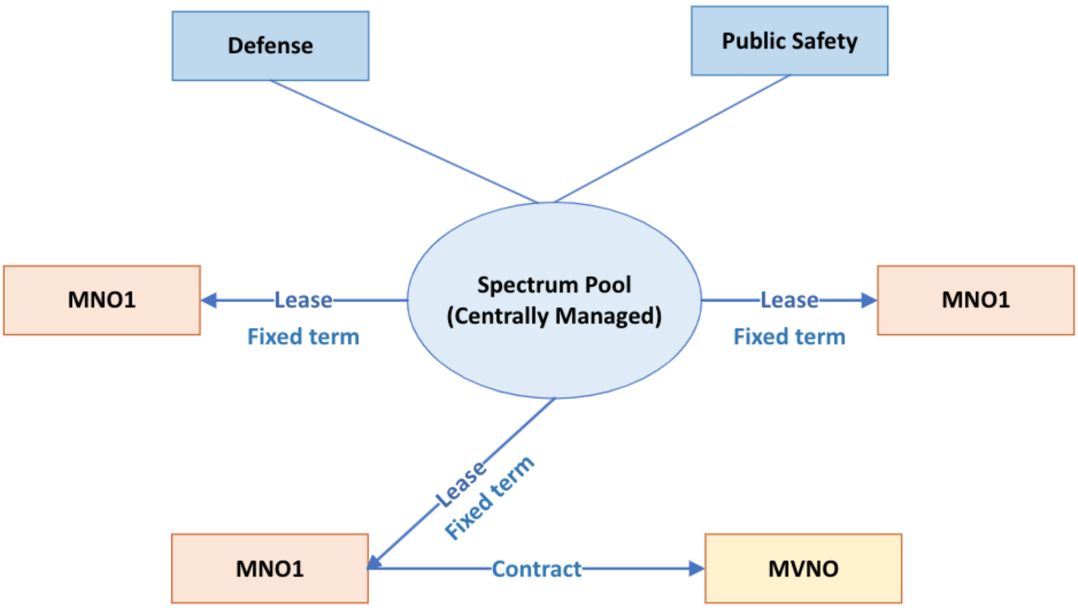

Fig. 2.2 Current spectrum landscape

2.2.2 Stage 1

The **Stage 1** represents the first pass of the architecture and is shown in Figure 2.3. At this stage all available spectrum is pooled (analogous to electricity pooling), and the regulator acts as the spectrum operator. At this point, the BYOS framework is introduced. BYOS has the following unique features:

- Quasi-static – Spectrum is offered for different time periods

- Categorised – Spectrum ownership periods differ for different categories of operators
- Prioritised – Some operators, like the Public Safety services, have the facility to gain priority access

Details of these features of BYOS are discussed in the next section.

In addition, three additional features are proposed that would make the system autonomous in the future. These features would ensure that regulators could take a hands-off approach to spectrum assignment.

- Tokens, to manage competition in the market. The idea is taken from, and is similar to managing traffic in networks
- Smart contracts, to automate the process of spectrum trading, providing trust and transparency between buyers and sellers, while maintaining efficiency and privacy (for maintaining competitive advantage)
- Short-term bilateral trading, where buyers and sellers trade spectrum over a fixed short-term period. The rights expire once the period expires and the spectrum reverts back to the original owner. Smart contracts ensure that the process is automated, while tokens are used for managing competition.

These features of BYOS are discussed in the Chapters 4 and 6 of the thesis respectively.

2.2.3 Stage 2

The **Stage 2** relegates the regulators to a hands-off role and the market becomes self-regulatory. This is shown in Figure 2.4. Three features highlight the expected maturity level of the system at this stage are:

- Bilateral trading between parties is extended to all periods (short, medium and long term) by this stage and as a consequence the buyers are now categorised giving rise to different ownership rights. (In Stage 1, only sellers were categorized).
- Regulators only enter the system if there is a specific request from one of the parties for arbitration e.g. if a concerned party reports that the spectrum purchase is underutilised and there is a demand for it in the market.

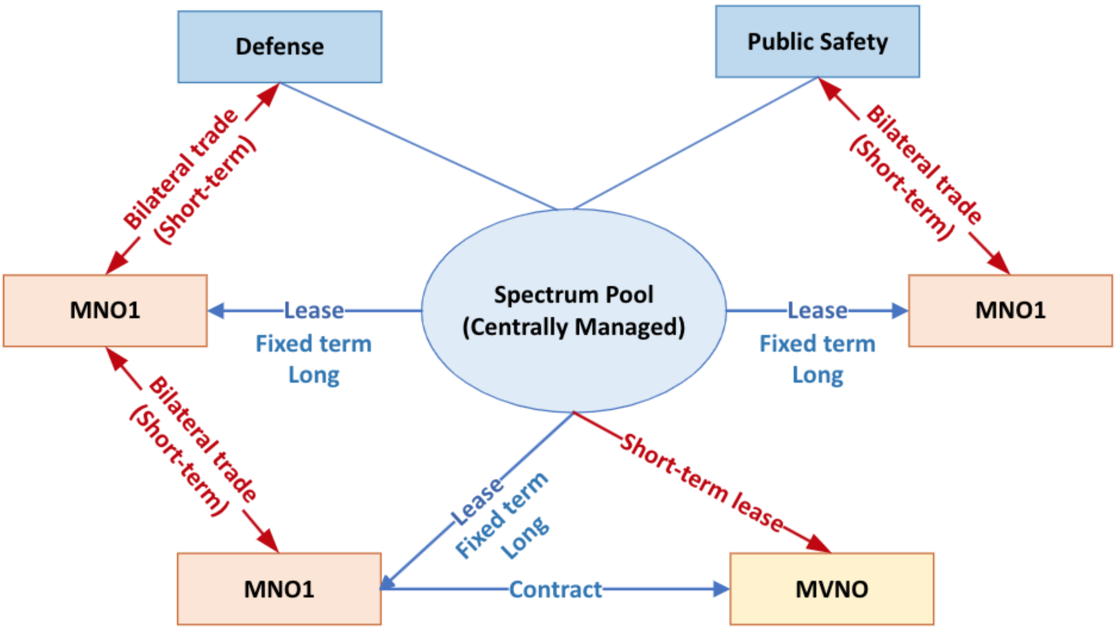

Fig. 2.3 Initial BYOS architecture
Red arrows: Short-term trading options, Blue arrows: Traditional central-pool trading

- The introduction of end units (EUs) to show that device level demand is now a possibility. That is to say, devices can collectively (as part of a cooperative) or through their existing operator put in a demand for extra bandwidth, which an MNO can then dynamically satisfy and charge for. The device can refer to mobile devices, household collective demand, or a femtocell.

2.2.4 Stage 3

The **Stage 3** is the blue-sky possibility i.e. when the market is deemed stable following its auto-regulation capability. At this stage other means of trading like options, futures (contracts and derivatives), sharing, private pools etc. can be introduced, first as a test over shorter terms. These can be subsequently introduced for longer periods, as the options are successfully validated. This part is out-of-scope at this stage is a part of the future work in this area.

Figure 2.5 summarises the process of BYOS adoption.

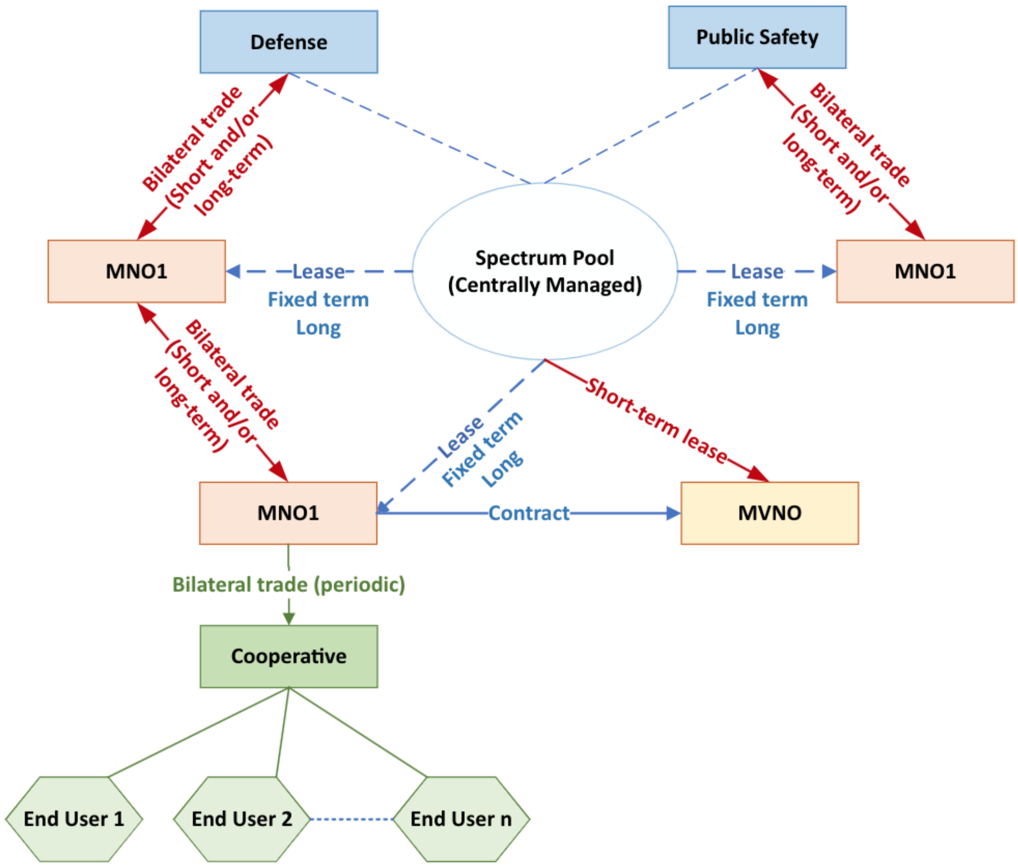

Fig. 2.4 Autonomous BYOS architecture
Green arrows: Device level demand

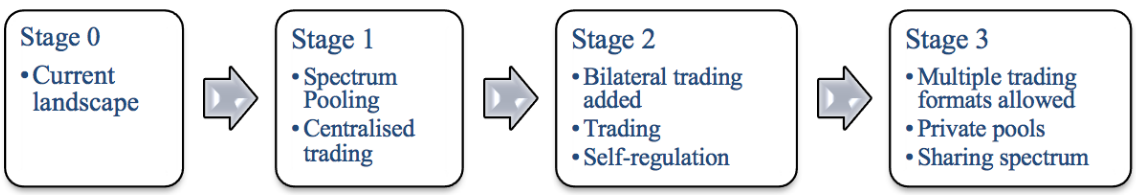

Fig. 2.5 Features of BYOS architecture through different maturity stages

2.3 Features of BYOS framework

2.3.1 Traditional static assignment

While spectrum demand is a dynamic function (depending on multiple factors such as time of day, number of consumers, data demand, technology used etc.), the underlying availability is constant over a 15+ year time frame. Thus, in these cases, the availability decides the demand and the availability itself is decided based on anticipated maximum demand and a large buffer. Two main drawbacks are:

- The provider has to stay within the speculated demand limits, as new spectrum is almost impossible to come by.
- The barriers to entry are very high for small and new users, for the same reason as above.

Under the current assignment framework, periodically a chunk of spectrum is made available in a band. Let the total available spectrum be S, which can be divided into N units each of size s (each unit referring to 1 MHz or 0.5 MHz of spectrum for instance).

$$S = Ns \tag{2.1}$$

Let k be the number of interested MNOs in a region: MNO_1, MNO_2,.....,MNO_k. Let spectrum won by the i^{th} operator be x_i, where, $0 \leq x_i \leq n_{max}$. After an auction the spectrum distribution can be shown in Equation 2.2:

$$S = \sum_{i=0}^{k} x_i + n_\delta \tag{2.2}$$

The term n_{max} represents the maximum spectrum that can be won by each operator. The maximum limits are decided by the regulator to either prevent monopoly/oligopoly or to promote competition by allowing smaller bidders to participate. The issue is that these maximum limits are arbitrary and are a major source of debate by both the industry and the academia. The term n_δ represents the amount of unsold spectrum during an auction. One of the key goals of the regulator is to ensure that this term is equal to 0 i.e. no spectrum is unsold. The common reasons why this might happen – an operator wins 0 units in a bid or withdraws or does not participate in the auction due to high reserve prices. This infamously happened in the 2013 spectrum auctions in Australia for the 700 MHz as part of the digital dividend.

Vodafone declined to participate in the Auction and the highly anticipated entry of Google did not materialise either [136]. This has been attributed to the high reserve prices set by the government[12]. Interestingly the 2013 auction was also when the MVNO, TPG Telecom decided to acquire spectrum, which many regarded rightly as a move towards becoming an MNO in the future [84].

2.3.2 Quasi-static assignment

The idea that there should be a periodic spectrum trading format is not new. Researchers such as [122, 143] have usually divided dynamic spectrum auction mechanisms into: periodic and online auctions. Periodic auctions, as the name suggests, are usually used to refer to auctions that are conducted periodically by the primary user (or a central auctioneer), and the interval between the auctions is relatively longer, usually $\geq$30 minutes. Online auctions, on the other hand, refer to auctions that are conducted whenever a secondary user arrives with a spectrum requirement i.e. in real time. However, these approaches are bottom-up and the auctions are conducted between the end nodes – either base stations or end nodes. Trading for longer times and for longer periods is not considered. In addition, as the researchers themselves have acknowledged, such methods are mathematically intensive.

The GSMA 2017 [144] report makes the stark need for new business models and new use cases for mobile operators quite clear, suggesting that the existing models and their extensions – despite being mathematically advanced – might not provide a complete solution to the problem of maintaining healthy competition and flexibility alongside a robust return of investment.

In this thesis, the spectrum assignment problem is viewed using a top down approach. This helps build a framework with a longer-term outlook, where node-based methods of auction and assignment are still applicable.

2.3.3 Proposed framework for spectrum assignment – BYOS

A flexible framework for spectrum assignment is proposed called Bring Your Own Spectrum (BYOS) – because it allows participants to be spectrum owners (regardless of their size). The system takes care of the spectrum ownership and trading limits. Following are the key characteristics of the BYOS framework:

- Quasi-static assignment with flexible ownership periods, classified into three levels.

[12] The spectrum was eventually sold in 2018, after lying unused for five years [84].

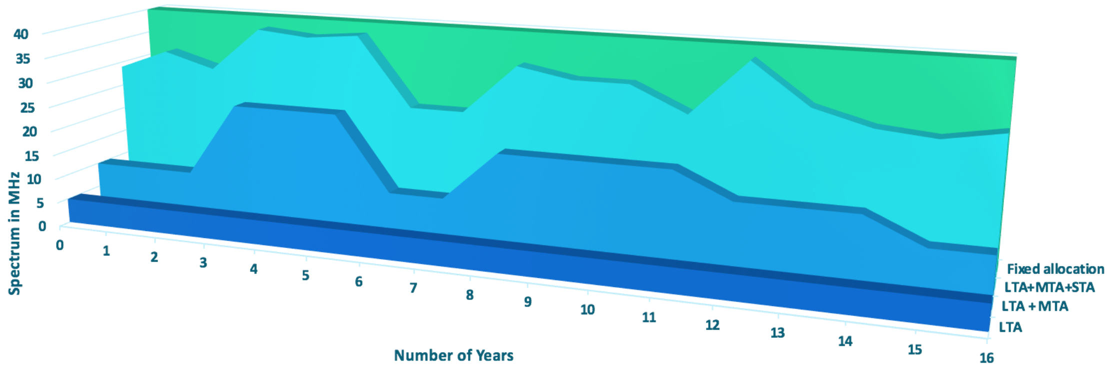

Fig. 2.6 BYOS - Quasi-static spectrum acquisition strategy

- Options on what exactly is assignedd to which operator (categorised operator types).
- Priority based assignment – Participants regarded as categories of agents with different objectives
- Multiple trading/sharing schemes allowed

While the framework is designed to be a one-stop spectrum allocation scheme, the present thesis makes several assumptions to while presenting the various aspects of of the framework:

- In this thesis, the discussion is limited to mobile services. Other usages of spectrum like wireless mesh networks etc. are not covered.
- Spectrum allocation, which refers to the use of a spectrum band for specific purposes is not discussed in this thesis. However, the thesis does contend that extremely strict and centralised harmonisation of spectrum also stifles innovation.
- Spectrum assignment, which refers of channel allocation to different interested users is the primary goal of the framework. However, the term channel it self is not the traditionally defined allotment of designated band of frequency usage.
- Fairness, which refers to fair competitive practises might mean several things – lower entry barrier for new entrants, robust return of investment possibility for highly infrastructure-dependent mobile network operations, paying market-prices for resources, assignment of frequency channels to parties that would use and value it the most etc. The term definition is broadly limited to fair competitive practises for this thesis.

- A key assumption is the availability of a spectrally agile radio for offering the services. The idea is that there is a 'black box' that theoretically allows radio operations. The discussion on the contents and processes of this black box is currently out of the scope of the thesis.

- Spectrum license refers to an operator license. The mode of operational usage is different at different levels of the framework, but all the licenses are assumed to be operator licenses.

The rest of this section provides a skeleton structure of the BYOS framework. The subsequent chapters will flesh out other aspects of the model.

Figure 2.6 shows the quasi-static model for spectrum assignment. The topmost section (represented in green) shows the standard long-term speculative spectrum acquisition model that companies currently have. The details of this have been discussed in static assignment part above. The sections in shades of blue demonstrate the quasi-static model of assignment for a company. Instead of holding a single big chunk of spectrum, spectrum can be acquired in three stages.

- **Long-term**: For satisfying the base capacity i.e. the base minimum spectrum that is required to run a network

- **Medium-term**: For satisfying the planned capacity within a region i.e. acquiring the spectrum depending on network design and technology used in a region. This type of holding allows operators to add capacity or to shed capacity/infrastructure to optimize capitaexpenditure (capex) and operational expenditure (opex).

- **Short-term**: For satisfying the peak capacity within a region. This part is where opportunistic models fit and spectrum can be held for periods as short as an hour.

Quasi-static model is defined in BYOS framework by setting up assignment periods. These are shown in the table in Figure 2.7

The model is defined as follows:

- Instead of once in a long-term auction (every 15+ years) or continuous/demand-based/real-time (like in a dynamic auction), auctions are conducted periodically.

- Each auction time period is pre-decided. Time periods are represented using a exponential scale of 2 (in hours, days, and years) to a max of 16 years (at this stage) – the

Assignment type	Ownership period	Assignment mechanism
Long-term assignment (LTAs)	16 years (2^4 years)	Periodically (assumed once in 16 years once the current ownership expires)
Medium-term assignment (MTAs)	8 years (2^3 years), 4 years (2^2 years), 2 years (2^1 years), 1 years (2^1 year)	Periodic auctions. For this thesis we assume a single 16-year period, with allocations at pre-specified periods. This replicates the current structure of spectrum auctions
Short-term assignment (STAs)	Hours (Potentially days and/or weeks)	Spectrum is allotted in chunks of hours: (a) Allotment doesn't roll over to the next period and (b) larger chunks can be allotted only at pre-set times.

Fig. 2.7 BYOS - Assignment and ownership periods

approximate timeline of spectrum ownership until recently. The scale was chosen because it was observed that the assignment periods in various countries over the decade can be expressed as a combination of the periods, in years. This scale can be easily adapted to shorter time periods, merely by changing the unit of time periods. Figure 2.7 shows the types of assignment, which have been categorised based on the length of assignment periods. Figure 2.7 also shows basic rules for spectrum assignment over different assignment periods.

- At the first time, it is assumed that the auctions are serially conducted – first available for longer time periods, then for progressively shorter time periods.

2.3.4 Long-term spectrum assignments (LTAs)

These assignments are reserved for stable network operators who have been providing the wireless sector for several years in a country. This advantage to the incumbents leaves them to plan their network for long-term access using the technology they choose. The assignment is on a first-come-first-served basis and has the following conditions:

- Allotted only once to each telecom operator.
- Allotted only to operators with multiple years of operating cellular networks in a country.

- As the MNO license is bundled with the license, only the regulator or government assigned this spectrum to the prospective operators.

- The quantity of spectrum allotted is limited to the amount required for basic network connectivity and mostly for signalling purposes. The operators (based on their experiences) are expected to demonstrate their requirements.

- The spectrum is bundled with the license (though each operator is expected to pay the equivalent license fees). The operators are also given the option to host other operators and their agreement/disagreement is reflected in the license cost and by other means

Note on bundling spectrum with MNO licenses

Bundling spectrum with licenses is not a new idea. In fact, this was the primary method for spectrum assignment in India from 2001 to 2013. Following the failure of the initial auction method to assign telecom licenses, the government introduced the new telecom policy (NTP) in 1999. Details of this policy are covered in Chapter 1. A key aspect of the policy was that the licenses were bundled with an initial assignment of 4.4 + 4.4 MHz paired FDD spectrum assignment for GSM in the 900 and 1800 MHz bands. On demonstrating efficient usage of existing spectrum, the operators could further be assigned 1.8 + 1.8 MHz spectrum. According to the regulator, the government was contractually obligated to provide 6.2 + 6.2 MHz to each licensee. The licensees were decided on a first-come-first-served basis [4]. The spectacular failure of this method is well known. Several researchers have published detailed analysis of the reasons behind the failure [2, 4, 3, 88, 89, 145, 1]. Following is a summary of the key reasons:

1. The rampant corruption in the process that awarded licenses to 122 licensees on a first come first served basis. The result was that about 70% of these licenses were awarded to companies that did not satisfy the basic eligibility conditions set by DoT and had also suppressed facts, disclosed incomplete information, and submitted fictitious documents.

2. The licensing process used licensing fee set in 2001 to assign licenses in 2008 resulting in substantial loss to Indian exchequer in terms of revenue forgone.

3. The policy was designed to accommodate the maximum number of subscribers under very limited spectrum availability using a single technology (GSM and later CDMA) for a large population over a significantly large geographical area. Prasad and Sridhar, in their critique of the spectrum assignment in India, discuss how limited focus on technical efficiency to assign spectrum was ironically highly inefficient [2].

4. The contractual obligation to assign spectrum to operators as it became available was also interpreted incorrectly. Instead of limiting the number of operators, or selecting them competitively, licenses were given to mostly all who asked for them making the network unviable. Even if the case is considered that there was sufficient spectrum, it was highly fragmented defeating the purpose of maximising usage.

None of the four issues, mentioned above, are expected to affect the existing scenario. First, mobile technology has come very far, allowing multiple technologies to exist together in a time-frequency slot. Most of the countries, including India, have made the spectrum assignment independent of the technology used for cellular communication. Second, in our framework the long-term spectrum will be assigned to incumbents, removing the possibility of corruption discussed in (i) and (ii) as well as network viability and efficiency (iii) and (iv). The mobile telecom operator landscape has matured in most countries and the stable market scenario has 3-5 main operators per geographical region as shown in Figure 2.1. The operators are also experienced and established in the market for numerous years, which means they have knowledge and experience to define their core spectrum needs with good accuracy. There is also no incentive to adopt corrupt practises because of these reasons. Thus, it is postulated that bundling an MNO licence with spectrum required on a long-term basis for basic network connectivity will be both useful and welcome. The operators would welcome this method because:

- LTA would allow the operators to gain some guaranteed spectrum for a long term (without participating in an auction).
- LTA would allow the operators to plan their network in the long term.
- LTA would lead to long-term market stability – a key point that is lacking in most dynamic system models.

2.3.5 Medium-term spectrum assignments (MTAs)

As shown in Figure 2.7, the medium term auctions are held for specific periods of ownership of spectrum. Following are the key aspects of this. The maximum period is about half of the traditional 15-year period, and the spectrum can also be owned for a period of 4 years, 2 years and 1 year. Spectrum during this period is assigned on a competitive basis, if the demand exceeds the supply. The assignments during this period actually reflect the current assignments conducted across the world using auctions or by administrative means (with a license fee attached). The assignment can be automatically extended for the next period if:

- No other party expressed interest in the same band – that cannot be satisfied by assigning channels in another frequency range.
- The existing party is agreeable to paying the license fee – decided based on the latest available pricing measures.

In addition to the standard central assignment, the following types of agreements (trading or licensing) are also allowed:

- Between Government agencies and Commercial operators
- Between the commercial operators

The caveat however is that the regulator remains a core part of the assignment. The objective is to ensure that customers are not adversely affected by ownership changes. The licensing rules can be decided between the parties. They can be of the following types:

- Exclusive use
- Shared usage between primary and one or more secondary owners
- Priority usage – e.g. exclusive/shared usage, until the primary owner (such as a public safety agency) requires the spectrum for emergency usage. Such conditions can be a part of the agreement.

2.3.6 Short-term spectrum assignments (STA)

As shown in Figure 2.7, short-term auctions are held for shorter periods of ownership – up to 1 year maximum (even 2 years as the market matures). The shortest period allowable under the framework is 1 hour, though technically assignment can take place for shorter periods.

This assignment can take place between the different nodes i.e. base stations (BS, nodeB or enodeB) of the network. The short-term assignment can be used for the following purposes:

- By incumbents and other MNOs to satisfy instantaneous or periodic peak capacity demands.
- By cognitive-radio technology-based operators to setup and operate their network. Ownership period can be extended when the network viability is determined.
- By public safety networks to satisfy instantaneous demand for emergency situations

By definition, spectrum is just one of the resources that allows the end users to communicate with others and/or access the Internet. Hence, it serves no purpose to extend the access of spectrum to individual end users. However, a collective of such users can theoretically install micro/pico/femto cells and purchase access to spectrum on a short-term basis.

Spectrum owned on a short-term basis differs from the standard long and medium term access in that this assignment does not carry over to the next period. This automatically means that the regulator does not need to be a part of the trading, except for oversight, arbitration and maintaining a database of trading for tracking revenues.

2.4 Similarity to other proposed systems

The idea of holding a spectrum portfolio with multiple-length periods has been covered in numerous papers, both from technical and financial perspectives. The discussion here focuses on three papers that present a complete model of hybrid markets – combination of long and short-term spectrum holdings. Kasbekar et. al. [146] first proposed a spectrum contract trading scenario with two types of contracts – Type-G or guaranteed bandwidth contract for long-term, which can be purchased for a fixed fee regardless of the usage and Type-O or opportunistic access contract for short-term purchased on-the-spot for a fee proportional to the bandwidth used, provided the primary provider is not using it. This model is somewhat similar to our model in that the spectrum contracts are based on the period of ownership.

This idea of the combination of guaranteed and opportunistic contracts has been subsequently explored in several papers. Gao et al. [123] also propose a hybrid market similar to above with the same two types of contracts. The guaranteed bandwidth contract is referred to as a futures contract with similar features but is unclear whether this type of contract is for a longer-term. The spot contract is said to be for spectrum demands in real-time based on opportunistic access. In our case, the short-term market is not necessarily based on opportunistic access, but is instead used to satisfy peak demands by operators.

Caicedo and Weiss [147] evaluate the idea of spectrum trading markets with and without band managers, and evaluate the case of trading spectrum without band managers. Several pooling strategies are explored in their spectrum exchange type model. The processes used for trading are similar to the ones proposed in the thesis, however, this model does not specifically address multi-period ownership. An extension of this paper is given in [148], where monetary units are added to model liquidity in spectrum markets. The auction mode is sealed-bid, second-price auctions and has designed the mechanism to assign certain units of spectrum between interested parties.

In their paper, de Carvalho et. al. [149] notably extend the idea into three types of contracts – Type I (guaranteed bandwidth regardless of usage), Type II (guaranteed, but with option to resell) and Type III (opportunistic access) contracts. This model is the closet to our model, though contracts don't clarify the period of ownership and do not allow the incumbents to participate in Type II and Type III contracts as a buyer. This omission essentially means the biggest and most efficient consumers are left off the market, which does not translate into efficient usage. They also pre-suppose that the primary operators always have spectrum to spare and would not require additional spectrum – an incorrect assumption, as spectrum scarcity is not limited to new operators but also incumbents looking to obtain spectrum to expand their network or offer new technologies for bandwidth hungry devices, as discussed in multiple reports. In addition to the work of researchers, a look at the recent types of licensing schemes show two emerging types of license frameworks:

- ASA/LSA: ASA (Authorised shared access) licensing scheme is specifically meant for spectrum that is previously held by governments. The license allows commercial operators to co-exist. Initial tests have been carried out for 2.3 GHz in the UK and 3.8 GHz in the US. The LSA (Licensed shared access) licensing scheme extends the concept of ASA allowing an incumbent mobile operator to share with one or more mobile systems without interference. Similar options have been made available during auctions, where a network agreeing to host competitors are offered spectrum at a lower cost. Both these are two tiered systems with the top tier reserved for an incumbent and the lower tier for general access by another operator [150].

- Spectrum access system (SAS): SAS is similar to the ASA/LSA licensing scheme, but is three tiered, instead of the two-tiered option for ASA/LSA. In 2015, the FCC introduced the licensing format for the Citizens Broadband Radio Service (CBRS) band i.e. 3.55-3.7 GHz to improve spectrum efficiency. The top tier of the incumbent system, same as in the ASA/LSA scheme. This tier comprises of the traditional government users of the band. The middle tier is restricted for priority access license (PAL) users, which can be another MNO and would be chosen based on the results of a bidding process. The third tier is the general authorised access (GAA), which provides lower access guarantees as compared to PALs. SAS allows GAA users to access the spectrum opportunistically [150, 151].

The proposed BYOS framework resembles the SAS scheme in some ways. The Stage 1 of our proposal can be thought to have a three-tier structure: incumbents, major operators and short-term opportunistic users. The middle tier has a guaranteed bandwidth for a comparatively longer term. There are key differences however, a notable one being that MNOs are also allowed to access the lowest tier. The competition is handled by external means – discussed in Chapter 4 and 5.

The logic behind this three-tiered scheme of spectrum licenses is sound and this also opens up the idea of opportunistic access to spectrum when underutilised. As usual, the difficulty occurs when issues of competition, monopolistic/oligopolistic concerns, preferencing big over smaller players or vice versa are taken into account. The FCC has already modified the rules and in 2018 proposed a solution as an "appropriate middle ground". The Chapters 4 and 5 of the thesis provide a potential solution to this issue.

Two stage markets are common in electricity markets and are mentioned in many of the papers discussing similar markets for spectrum. The differences and similarities between spectrum and the electricity markets are particularly interesting and guide the next stage of our framework. They will be discussed in Chapter 3.

2.5 Assignment by operator type – Categorised

Incumbent operators can purchase their operator licenses with a basic long-term assignment that allows them to plan the network on a long-term basis. Following this, the operators can then purchase spectrum on medium term(s) to operate a commercially viable network that can also be planned on a longer term. The potential availability of spectrum on a periodic basis will also allow the operators to save on holding the spectrum costs and expand their network based on pragmatic extrapolations. In case the operators require spectrum to satisfy peak capacity requirements, then the spectrum can be acquired on a short-term basis. Thus, spectrum holding for operators now changes from a big-fixed-chunk over a long-term to a more flexible demand-based ownership.

If the market comprises of i number of operators, the spectrum ownership for the i^{th} operator can be represented as follows:

$$S_i = S_i^{LTA} + \sum_{t(years)} S_{it}^{MTA} + \sum_{t(weeks,days,hours)} S_{it}^{STA} \tag{2.3}$$

For all operators, other than the long-term incumbents,

$$S_i^{LTA} = 0$$

. The term t refers to time in years, weeks (w), days (d), and hours (h). The regulator can increase the number of incumbent operators, if they can satisfactorily demonstrate continuous national level operation for a period at least equal to one LTA-period i.e. 16 years.

The period for medium term assignment i.e. MTA-period is in years. The assignment under this heading can automatically roll over to the next period (when there is no demand by another MNO) and replicates the current spectrum landscape. The spectrum is assigned for shorter periods (<1 year) i.e. STA, either to satisfy peak capacity or is intended for MNOs/MVNOs relying on frequency-agnostic techniques to operate their network. STA assignment does not roll over to the next period and the period of assignment can be in weeks, days or hours.

Figure 2.8 below shows how the different assignments fit together for an incumbent MNO

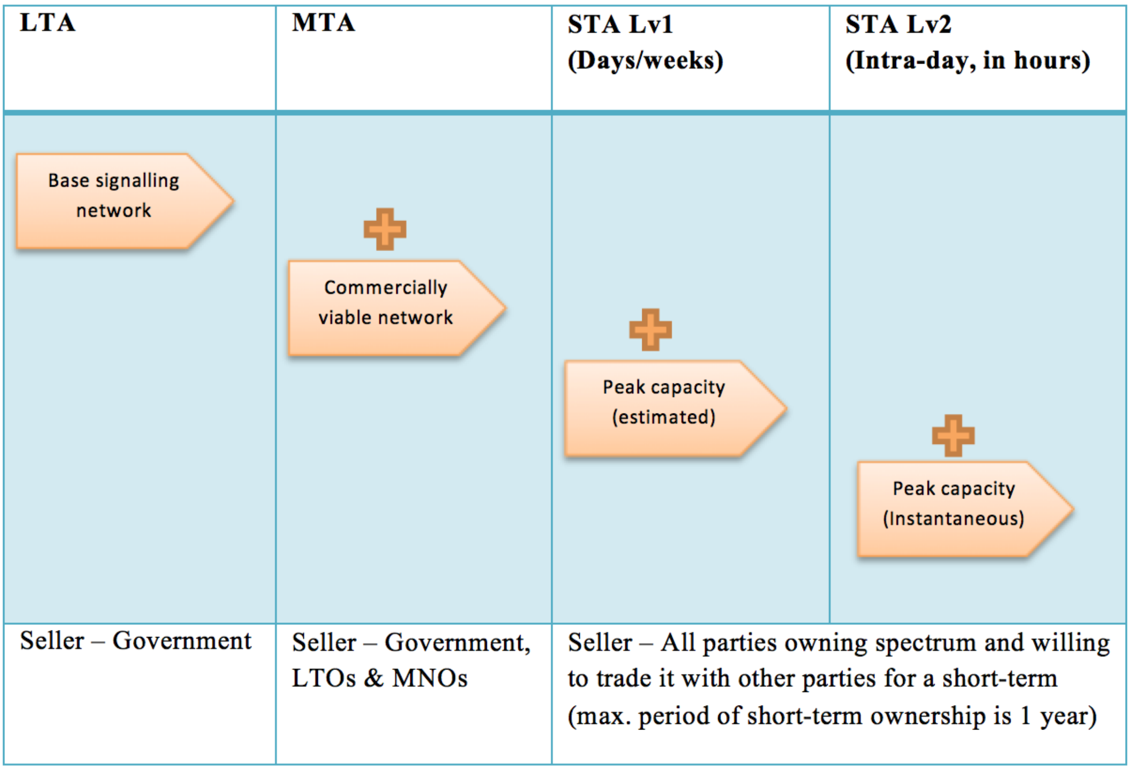

Fig. 2.8 BYOS - How spectrum assignments fit together

In this thesis, a concept of spectrum as a service (SaaS) is presented by equating spectrum with capacity. In reality, capacity is a combination of spectrum + infrastructure that an operator assigns to achieve desired capacity. Spectrum is essentially a part of the capital expenses of a mobile operator (capex). Infrastructure, in contrast has both capital and operational implication (opex): the cost for purchasing the equipment is capex and the cost for operating the equipment, network operation in general and maintenance expenses are part of opex. Both the spectrum and infrastructure can be a part of the service economy. The latter is represented as infrastructure as a service (IaaS). Figure 2.9 and Figure 2.10 show this combined form of sharing – this is expected in the real world.

The present work leaves infrastructure out of subsequent discussions. This is because spectrum is the only one resource that is classified as a limited or scarce resource in space and time. It is a public resource, cannot be generated or produced, and contributes billions of dollars to the economy as a direct result of sale to limited parties.

The Equation 2.3 shows assignment over a flexible period. Two ways for this assignment scheme to work are proposed:

Active		Passive	Backhaul
Spectrum (radio waves)	Active Infrastructure *e.g. antenna, transceivers, microwave equipment, switches*	Support infrastructure *e.g. power supplies, batteries and generators, heaters and air conditioners, towers and housing for BTS, safety equipment*	Core network modules *e.g. transmission equipment, links between core network modules, mobile switching centres, switch nodes*
Radio waves	All Infrastructure		

Fig. 2.9 Mobile telecom network infrastructure

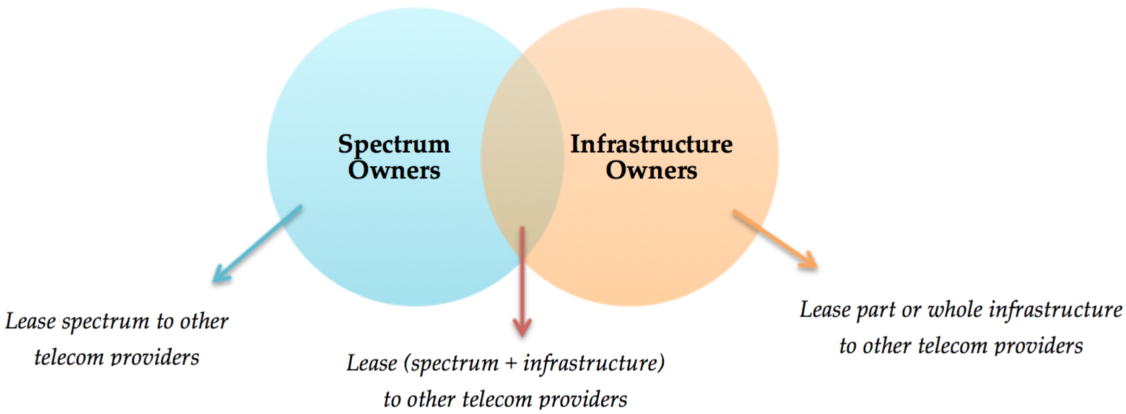

Fig. 2.10 Types of sharing

- Method I: The assignment is done by the standard channel-assignment scheme. The long and medium term assignment is done by assigning spectrum in the traditional way
- Method II: The assignment is done by considering the level of noise in each channel. This determines the channel reusability in space and time. This information can be used by other interested parties to opportunistically use the channel.

2.6 Summary of Chapter 2

This chapter introduced a new framework for spectrum assignment. First, a discussion was presented on the need for a new framework. The discussion also provided information on the features of the framework such as allowing non-interventionist oversight from the regulator, agnostic to technology type, and allowing trades between different types of buyers and sellers. The proposed framework BYOS offers all these features and additionally also allows flexible spectrum assignment periods, unlike the current system where spectrum is only sold over a long-term period. These features would serve to reduce entry barriers, allowing greater competition in the market. A unique model of quasi-static period of assignment was introduced for this purpose that allows multiple categories of ownership periods. Operators types are a natural fit into this architecture and categorisation is often dependent on the period of ownership. The model was compared to other models proposed in the literature. Finally, the dynamic of spectrum-infrastructure was discussed in terms of how it fits into the existing framework. The internal features of the framework and detailed working processes are discussed in the subsequent chapters, starting with a proposed trading unit for the framework in Chapter 3.

Chapter 3

Noise

This chapter presents the technical backdrop of this thesis. Based on the requirements of the telecommunication sector, and consequently the framework, there is a need to review the physical resource to be traded. The chapter starts by discussing the ownership aspects of spectrum and restriction due to the current modes of ownership. Following this a discussion on spectrum resource and its uniqueness is presented, to better understand its distribution between interested users (buyers). A brief literature review is then conducted on the work done by other researchers in determining a new trading unit for the spectrum resource, which is followed by introducing the emissions-based trading unit proposed in this work. The trading unit is refined by including additional parameters. The chapter concludes by discussing the ways in which the proposed trading unit can be used by participants in the framework.

3.1 Ownership of spectrum resource

The traditional assignment of wireless spectrum is by way of offering exclusive usage rights in a frequency band, though there are some bands where spectrum is shared between different users. Spectrum is managed using a command-and-control approach, where terms of usage are carefully stipulated and closely monitored. Commercial assignment predominantly comprises of granting spectrum to wireless service providers for a fixed period of time.

Until a decade ago, governments in most countries also stipulated the technology to be used. The increase in demand for data that necessitated a need for spectral efficiency has led to more regulators adopting the principle of "technology neutrality" while assigning spectrum to mobile operators. However, this does not mean that mobile operators are free to do anything they like within the frequency bands they are assigned. Operators are still bound by rules that limit negative externalities such as radiation limits and radio interference to other operators. In addition, the frequency bands are harmonised at an international level and particular bands are identified for specific usage at a global or regional level. Following this, standards are developed by the 3rd Generation Partnership Project (3GPP) for how radio equipment can be operated in these harmonised bands [152]. This basically means that current regulation allows only standardised technology in designated frequency bands.

The development of technology has ensured that regulators have ceded more control to operators (i.e. market forces) to choose the technology to be used in the bands assigned to them. Technology trends clearly indicate a move towards more intelligence that requires much less directive control. It is not hard to envisage a future world, where radio networks would be self-organised to the extent that the process of regulation between different operators would be automated. The dynamic spectrum access framework proposed in Chapter 2 is an attempt to restructure the current framework, so that the regulatory structures are more responsive to cognitive networks of the future.

A part of the dynamic access framework is the flexible time approach. This has been discussed in the previous chapter. This chapter addresses the issue of ownership in the wireless radio systems.

3.2 RF Spectrum – A unique resource

Wireless communications are enabled by the management of two fundamental resources – energy and RF spectrum. Design of wireless systems generally involve optimising the usage of one resource over the other. Energy efficiency is a key issue in modern wireless communication given that as mobile devices add more functions, they become more energy hungry. Energy management and trade-off with spectrum resource is however out of the scope of this work. For this thesis, the focus is on spectrum management and efficiency.

Spectrum is unique, when compared to other natural resources in the following ways:

- It is not consumed, it is instead used as a medium
- Exactly the same amount of resource is available regardless of the location – the economics of usage depends on cost of infrastructure and number of users
- The resource has three dimensions: space, time, and frequency – all interrelated
- Impurity of resource is a measure of interference, which can be from both natural causes (cosmic noise, lightning etc.) or manmade causes (generated by transceiver electronics of the target or rival systems)
- It is a wasted resource, if:
  - It is assigned to a party, but not used
  - Resource assignment is insufficient or inappropriate with respect to the application for which it is intended
  - Resource is underused, but other technologies can get more efficient usage or technical outcomes

Several options have been considered to assign spectrum and set the price of the resource used. The best known model for spectrum pricing was adopted by ITU in 2003 [153]. This is shown in Equation 3.1:

$$P = \frac{V}{M} \times \frac{K_f K_s}{K_m} \times C_s \times K_p \tag{3.1}$$

Where:

P = Spectrum price

V = Volume of space or geometric area occupied

M = The number of channels to be provided or users to be served (depending on the radio equipment or application)

K_f = Coefficient reflecting specific characteristics of range used

K_s= Coefficient taking into account the region of the radio station installation

K_m= Coefficient reflecting social benefit of radio system

C_s= Annual spectrum management costs

K_p = Coefficient reflecting the level of spectrum access demand in the band in question

The advantages of the above model is that it can be used to simulate more efficient use of spectrum. However, the formula is difficult to use in practice because the coefficients are hard to define and vary on a case by case basis depending on the system application, spectrum demand and the revenue potential. Other spectrum pricing models include setting prices by market methods such as spectrum auctions or by setting administrative prices equal to the opportunity cost.

The latter method of spectrum pricing is known as administrative incentive pricing (AIP). Prices in the AIP method are calculated by estimating the additional cost an operator has to put in to produce the same service using incrementally less spectrum in a band or the spectrum in the next cheapest band or with a non-wireless option such as a fibre-optic cable. These extra costs measure the loss of opportunity to use the spectrum in question. The measurement variables using this method are: economic and demographic variables e.g. population density in a region and return of investment etc.; market parameters e.g. market share and traffic etc.; technical network and deployment; network costs; base station parameters such as distribution and coverage; and radio spectrum parameters relating to the availability of spectrum in different frequency bands.This method is used by OfCom in the UK and by ACMA in Australia.

Regardless of the method used for spectrum pricing, the purpose remains the same – identifying one or a set of technical parameters to measure the volume of spectrum used or to determine the "pollution area" of a radio system as a common basis for establishing spectrum fees. This latter analogy is used to develop a model for spectrum pricing as a variation of the formula given in Equation 3.1 above.

3.3 RF spectrum as multi-lane highway

For the remaining part of this chapter and discussions in later chapters, the basic model spectrum pricing mentioned in Equation 3.1 is used as the reference model.

The equation has been deemed problematic for practical applications, as the constants are difficult to identify and vary across different usage cases. Until recently spectrum bands were strictly fixed for specific purposes, which made the assignment process simpler. With the advent of software defined radios, multiple technologies are able to integrate within a frequency band, necessitating a need for change in the way spectrum is viewed and assigned.

In fact, from this perspective RF spectrum is similar to a multi-lane highway connecting two geographical locations, transferring goods/people between the locations. Different types of vehicles, with widely varying attributes, objectives and motivations, share the highway at the same time. This is similar to packets of information travelling through different frequency bands. This analogy is used to propose an alternative spectrum management scheme. The similarities between the two concepts, discussed below, helps identify the unit for trade and handle issues like competition and network traffic management. In this part, a discussion is presented on the analogy highlighting the similarities between the two areas, differences in their ownership and management, and extension of these ideas into spectrum management. This discussion ties into the parameters of Equation 3.1.

Figure 3.1 below shows a multi-lane highway with marked lanes and bidirectional traffic.

Fig. 3.1 Multi-lane highway with marked lanes and bidirectional traffic [154]

Similarities between a highway and RF spectrum

- **Division into lanes**

  Highways are divided into multiple lanes as shown in the Figure 3.1. Each lane is earmarked for specific use. The lanes are mostly interchangeable but are clearly assigned to avoid confusion, and hence collisions impeding traffic flow. For instance, there are distinct group of lanes for traffic moving in each direction. Often one of the lanes is earmarked for larger or slow-moving vehicles. The lane at the opposite end from the slow-loving lane is the fast-speed lane, and usually is used for overtaking vehicles moving at the prescribed speed. The speed of vehicles is also directed by the regulator and can be changed given adverse traffic, road quality, weather conditions.

RF Spectrum is similarly divided into separate bands for a given frequency range and assigned to an operator. There are separate bands for uplink and downlink communications, though they are interchangeable. The assigned frequencies are separated from each other by guard bands. Like roadways, spectrum is used to transfer information from one point to another. When not in use, the spectrum band would be free (like a reserved lane on a highway) and can be used by other users, provided the lane is cleared when primary users need it. This forms the basis of the current LSA/ASA type licensing schemes. In Equation 3.1, the parameter M represents the channel divisions.

- **Classified based on characteristics**

  Highways or Roads can be classified in several ways – location/function, traffic volume, width, traffic type, cost of building, rigidity, topography and materials. The last of these classification factors – materials used for building the road – is a characteristic of the road that determines what it would be used for – function, traffic type and volume, and topography for which it is suitable. Features such as rigidity, width and ultimately cost of construction are decided based on function and level of usage.

  RF Spectrum similarly has different propagation characteristics for frequency bands, which decides what type of application they are suitable for. (While the basics of free-space propagation are consistent across all frequencies, the environment in which real-world radio applications work is highly dependent on the specific frequency used. Propagation medium, distance of travel and obstructions in the travel path are the basic operational conditions that determine the best frequency bands for an application. Applications examples include television, radar, deep space communication, radio communication etc. The technical solutions are then evaluated for their economic feasibility before a radio system is designed. Theory of developing network backbone is decided based on the importance of application and/or the number of users that would be using the channel for communication. In Equation 3.1, the parameter K_f represents band characteristics, K_s represents the characteristics of the location/region, K_p represents the demand in the band, and K_m social benefit of the radio system.

- **Ownership and usage**

  Highways are public property and usage is regulated by the government. They cannot be owned and are immovable. Users merely use them as a medium to transmit people and packages from one point to another.

  RF Spectrum is also considered public property. Spectrum cannot be owned and is immovable and can only be used as a medium of communication. As discussed in previous chapters, pioneering governments throughout the world ensured that the radio spectrum is considered a public property and all the other are merely temporary leaseholders of the band. Exceptions to this are Guatemala and El Salvador, where radio frequency is treated as a property (to be used and sold as desired) for a fixed period. Following the expiry of this period, the spectrum bands revert to the government, which can then decide how to reassign the spectrum to interested parties.

3.3.1 Ownership and management of Highways vis-a-vis RF spectrum

As discussed, the price P in Equation 3.1. reflects per unit licensing cost. The parameter C_s reflects the party responsible for developing and maintaining the infrastructure. This is where the roadways and spectrum differ, in terms of who pays for the infrastructure-maintenance-management costs and how it reflects the idea of usage of the medium.

Roadways have a clear distinction between infrastructure and usage rights. Infrastructure building is the responsibility of the government (local or federal). Private contractors charged with the building of roads may either get paid by the government or come into alternate arrangements such as fixed-term toll booths to recover their costs. Eventually all the roadway's related infrastructure belongs to the government. The built infrastructure also cannot be leased to private operators. Everyone has equal rights to access and the cost is recovered via taxation at various levels.

Spectrum, in contrast, is leased to interested operators, who build the infrastructure around the frequencies allotted and try to recover the investment by in turn selling the usage rights to end users in the form of applications. Other operators are barred from using the spectrum band till the lease expires, which is calculated based on the time to recoup a return on investment. By and large, the spectrum pricing model has worked in the past because it was not possible to share spectrum in any meaningful way, due to technology limitations. Because of this, the infrastructure was also intrinsically linked with the spectrum bands allotted. Regulation of the bands also promoted this form of ownership. However, technology has advanced to the extent that not only is it possible for operators to move the data packets (information elements) across different lanes, but also share the lanes with other existing users (in space-time) without losing information packets.

The proposed framework for spectrum usage postulates that the infrastructure building, could and probably should, be separated from the operational cost. Any operator who builds the infrastructure does not necessarily need to recoup the entire investment by operating the network on their own. They can allow other interested participants to enter their network and use the resources to deliver their service – similar to mobile virtual network operators. Or they simply allow the space (i.e. radio spectrum) to be used without offering any resources. The cost can be offset either by means of internal payment or by making sure that the primary owners pay less for the band. Mobile operators can also expand and reduce their running costs by offering services for a shorter period of time, relative to the demand.

3.3.2 Strategy for future-proof wireless network design

Telecommunications are gaining equal importance to other core nation-building infrastructure such as the roadways and highways. Lack of proper transport infrastructure adversely affects the exchange of goods and services underpinning a modern economy. Hence, the cost of building this infrastructure is derived from general taxes. The demand for infrastructure is not direct, but it is driven by the demand for other goods and services that in turn need a more efficient transport system. Telecommunications, in line with erstwhile post and telegraph services, are also considered crucial to national economy. Hence, most countries have now adopted Universal Service Obligations (USO) in the telecommunications sector with several in the process of extending this to broadband communications. Like roadways, USO obligations are also funded using general taxes.

As penetration of mobile phones is nearly saturated in many parts of the world, the concept can logically be extended for mobile infrastructure. This would mean that the development of mobile communications infrastructure should be under government oversight and payable using general taxes. This is one of the potential ways to permanently delineate mobile infrastructure from spectrum. One of the key assumptions of this work is that infrastructure development focus should be on the development of a centralised wireless network infrastructure supporting an intelligent radio system that can be adapted to changing demands in space and time. Network virtualisation and infrastructure-as-a-service are steps in this direction. Spectrum – as it is a resource on top of the infrastructure – is then purchased/leased by interested operators/users based on the market-based demand and supply conditions.

The infrastructure solutions that would satisfy the need for an adaptable and ubiquitous network are beyond the scope of this work. In this work, it is assumed that the mobile network infrastructure will eventually move towards the goal of being fully adaptable to changing space-time-demand requirements. This work focuses on the acquisition of spectrum – a scarce resource – based on real-time demand and supply conditions.

An additional benefit is that modern technology in radio communications has advanced to the extent that multiple operators can theoretically share frequency bands. This was one of the key technological barriers that solidified the need for a neutral party controlling the assignment of spectrum. This meant than interested operators had a fair chance purchase the spectrum required. Cognitive radio changed this by allowing operators to share the use of the same frequency bands. Spectrum sharing can be done using one of the following techniques:

- **Underlay** – Technologies such as ultrawide band technologies make use of underlay technology. Both primary and secondary users can transmit together, but secondary users transmit at a lower power to avoid interfering with the primary user communication [155, 156]. This is analogous to making use of carriage space under vehicles to send information from one point to another. Imagine a fleet of drones flying under the carriage space.

- **Interweave** – Another set of technologies make use of their knowledge of the primary users and use the dynamically created holes in space and time to transmit information. Secondary users use sensing to realise when primary users are not transmitting and use these period to transmit their information packets. Primary and secondary users never transmit together [157, pg. 47]. This is analogous to sleek vehicles like bikes zipping between the existing larger vehicles on the road in order to transmit information.

- **Overlay** – Overlay paradigm is a newer type of spectrum sharing technique. Here, secondary users are aware of the primary users codebooks and messages. They coordinate with the primary users to send their information using the same channel as the primary users and at the same time. They are also free to use any level of power, so long as they provide the primary user with some guarantee either in the average Signal-to-interference-plus-noise ratio (SINR) levels or primary user throughput. Secondary users may even use their service period to send primary user data packets to achieve their obligations to primary users [155, 156]. The best analogy for this could be a secondary user coming to an agreement to share a lane with a primary user and sending a fleet of vehicles that would be sent at pre-decided intervals and will carry some agree-upon payload for primary users.

Figure 3.1 below depicts the three types of techniques.

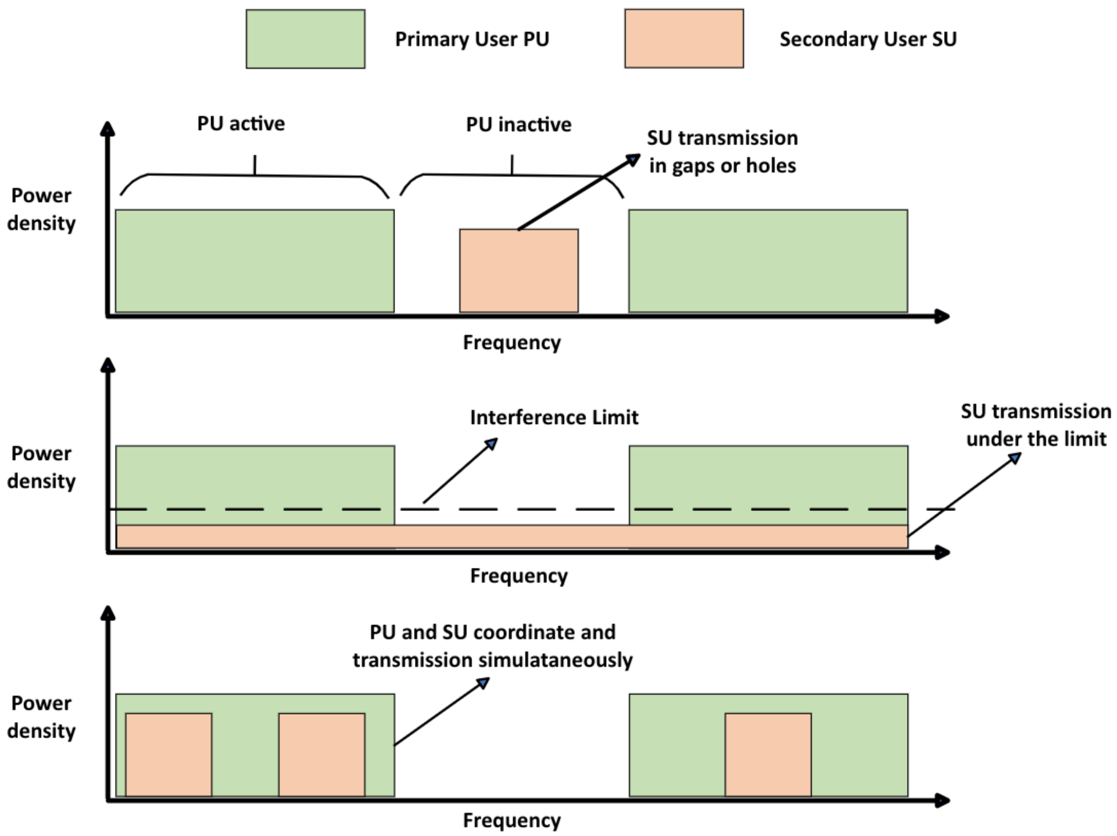

Fig. 3.2 Mechanisms used for spectrum sharing, adapted from [158]

3.4 Trading units in the framework

Ronald Coase's [47] proposed idea of market-based spectrum property rights is chosen as the basis of many cognitive radio research papers. The primary take from Coase's proposal is that spectrum rights should be assigned using market forces and that instead of assigning spectrum on demand, regulators should award it to the party that values it the most. The idea was widely derided when it was introduced, but ironically represents the current spectrum assignment trends throughout the world. The original proposal by Leo Herzel [49] pointed out the interesting debate that public safety services such as the police should compete with other users (in those days broadcast users) for resources. The problem extends to government agencies like defence and other reserved bands and has remained a source of contention.

This discussion related to the $\frac{V}{M}$ parameter in Equation 3.1. As applications and objectives change, it is difficult to assess whether M should be considered in terms of channel or population or a combination of both. And what exactly is measured using the volume/area variable V? Software defined radio shows the direction towards a convergence of multiple technologies, so arguably there should be a common set of variables to measure spectrum holding. As frequency occupation means different things for different technologies, exclusive long-term occupation with property rights is problematic, as can be seen in Guatemala's recent legal issues with spectrum reassignment for 4G [91].

While spectrum licenses are a de facto private property, the spectrum assigned to licenses is not – and this has been the case since early 1900s (1926 in the United States, after a court case). Regulators, even during auctions offering exclusive rights, only sell licenses to use approved devices to emit radio signals. As seen in Section 3.3, RF spectrum is a medium used to connect transmitters and receivers facilitating communication between them. The possibility and requirement for multiple technologies and companies operating on a single frequency band makes it harder to justify long-term channel occupation rights. In this section, a discussion is presented on alternative spectrum resource trading units and the merits and demerits of using *noise* (or interference) as a trading unit.

3.4.1 Alternative trading units

Determining an appropriate trading unit is a central theme of dynamic spectrum access research. There have been a multitude of papers that have in turn spawned several surveys compiling them. The studies [124, 125] have complied the information into systematic studies, exhaustively covering spectrum-related opportunities proposed as trading units. A summary is presented below:

- Frequency bandwidth: This approach involves one or more primary users trading/sharing spare bandwidth with secondary users

- Power: This approach involves one or more primary users charging secondary users based on their power levels. It also acts as a constraint and the secondary users can be admitted only if the power levels are under a certain interference constraint (similar to CDMA systems)

- Time: This approach involves one or more primary users selling spare slots in a TDMA system, so the secondary users are able to access unused time slots to send their information. Thus secondary users are able to use the frequency bands for a dedicated transmission time for their own data.

- Transmission rate/capacity: This approach involves one or more primary users selling spare capacity to secondary users. Often the data packets of secondary users are sent with the data packets of primary users and rates are based on successful transmission per time slot.
- Channels (either unspecified or a combination or one or more of the above resources): The term refers to spectrum opportunities in space and time. Many times the above resources are used interchangeably to describe a channel.
- Admission to the system: This approach was mentioned in a few papers, but a review of the paper shows that the primary users or regulators sell ‘channels’ to maximise revenue or some other utility to the best possible outcome.

An underlying question in this context is also the "payment" offered by the buyer and received by the seller. Most of the trades involve direct payment though the survey above has also determined several studies where researchers have proposed alternatives such as secondary units offering the primary users cooperation in terms of coverage, battery life and/or throughput of the primary licensee. In such a format, the secondary users act as transmission relays for the primary nodes [124]. While barter systems of any type attract a commensurate capital gains tax in several countries, researchers have also proposed alternatives to money [124, 125]. In this thesis, it is assumed that the payment would be in the form of monetary reimbursement and bater and other alternatives of payment are not considered. The framework does allow tracking overall trading units in the form of tokens (discussed in Chapter 4), which can be used in future if alternative forms of payments are considered.

Each of the assignment scenarios has one or more system constraints as well. A few surveys have also listed the various constraints [146, 158, 124, 125, 159]. These are listed below:

- Minimise one of the parameters below:
  - Interference/power at the expense of individual user Quality of service (QoS) demands. The criteria used by many is the interference temperature limit (ITL)
  - In tandem with efficient routing to minimise either total end-to-end delay or switching delay at the expense of network performance and/or interference to the primary users

  - Energy consumption of secondary users while meeting their QoS needs at the expense of overall system (SU network) performance
  - Minimise risk of path blocking by primary users at the cost of system performance and spectrum utilisation (due to simplified single-channel models), though handovers are minimised as a by-product.
  - Maintaining network connectivity (usually in cognitive ad-hoc networks) by minimising interference at the expense of QoS of the users, network performance and spectrum utilisation.

- Maximise one of the parameters below:

  - Spectral efficiency i.e. spectrum utilisation in terms of either channel usage or number of secondary units served. This is done at the expense of individual secondary user requirements and can be achieved only within a centralised architecture
  - Either user or network throughput in both centralised and distributed architectures at the expense of increased interference or fair distribution of resources between different users. There is the possibility that one of more users experience the 'starvation problem'
  - In contrast to the option above maximising throughput/spectrum distribution solves the 'starvation problem' at the expense of network performance and QoS requirements.
  - Revenue maximisation of primary users at the expense of network delays caused as a result of dynamic price discovery measures, unless there is apriori knowledge about cost per band across different users.

3.4.2 Interference as a trading unit – background

Interference (SINR) is usually treated as a constraint, not as an item for trading. In fact this is the primary constraint posed in the development of most of the frameworks of dynamic spectrum access. However, a select body of research also argues that interference itself could be a tradable commodity. The idea here is that instead of choosing exclusive rights, such as property, the interference defined 'as a right to degrade a resource' can be chosen as a tradable commodity. The resource degraded here is the spectrum frequency band but this does not necessarily degrade the QoS. Here, a background of the research done in this area is presented.

The idea was first proposed in 2002 by the Spectrum Policy Task Force (SPTF) in US, when introducing the (now defunct) concept of interference noise temperature [160]. In the initial version, the interference noise temperature was not treated as a sharable or tradable commodity but a means of implementing a new trading/sharing approach. The objective was to enable a way to allow spectrum sharing by making use of the underlay paradigm. The FCC postulated that there is an interval between the original noise floor and the licensed signal of incumbent services that could be exploited by secondary services to transmit signals using techniques such as ultra-wide band and code division multiple access techniques. The approach lost momentum about 5 years after it was proposed, because interference noise temperature for required transmission was a complex parameter to measure and quantify distinctly from that generated from other background and atmospheric sources.

OfCom then took up the idea of spectrum usage rights in 2006 [130]. This was a part of their strategy to move away from the strict command-and-control regime to a market-based approach. The point raised was that the current licenses control interference indirectly, which is problematic if different technologies operate adjacent to each other competitively. OfCom hence suggested that instead of licenses specifying the type and level of signal transmitted, they should specify the interference a license is allowed to cause. This type of license would be technology neutral as technologies of any type are allowed so long as the maximum interference to the neighbours remains unchanged. OfCom later expanded this concept by introducing the idea of a lookup table that can be used to determine the interference levels corresponding to mobile node density and power levels (power flux density PFD, to be specific).

Weiss [161, 162] extended this idea to develop a new scheme of interference rights, which is the basis of the work done in this thesis. Weiss's proposal is use noise as pollution. That is to say, if one user is using a channel, they create pollution for all other users intending to use the channel or operating in nearby channels. This also ties in to the multi-lane highway analogy discussed above. If an operator makes use of a lane, other interested operators cannot use this channel and have to wait till the channel clears or have reduced throughput.

As mentioned earlier, spectrum channels are mediums to transfer information from one location to another. Every time the medium is used at a point in space-time, that part becomes unavailable for use by other parties until the user leaves the space. In the case of spectrum, this idea is perfectly captured by the idea of "polluting the spectrum band" similar to air pollution. This means anyone gaining the right to use the spectrum is essentially gaining the rights to pollute a particular set of frequencies for a pre-set period of time. Exclusive ownership allows 'owners' to pollute assigned spectrum bands at theoretically infinite levels.

In reality, the pollution level is limited because the central node (base station) has to cater multiple end users i.e. customers in the same region accessing the same spectrum for communication. Maximising the throughput shared between users is the goal.

For this work, the focus is on emissions based assignment for assigning spectrum. The sections below discuss various aspects of this type of assignment scheme.

3.5 Emissions-based assignment

Emissions based assignment is an approach that takes its premise from mechanisms to manage air pollution. Air pollution is an inevitable outcome of any production or economic activity. The right to emit is essentially like permits that can be traded/sold/shared with any other entity in the system. The permits exist and expire in real time. Figure 3.3 below shows types of emissions in the context of air pollution.

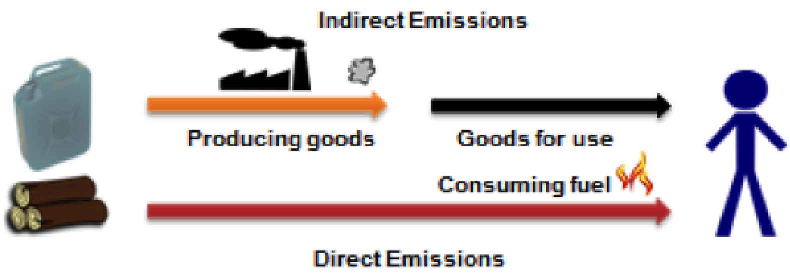

Fig. 3.3 Types of emissions in air pollution

Regulators have tested various measures to create an incentive to reduce pollution – the main goal of emissions trading. Air pollution management measures can be categorised into two [161]:

- Price-based measures where polluters are encouraged to reduce emissions by means of taxes or subsidies, and
- Rights-based measures where qualified or registered polluters are given rights to pollute in terms of credits or permits that can be traded with other parties.

Before continuing the discussion on emissions, a clarification of key terms – noise, emissions, interference – is necessary. The terms obviously refer to different physical quantities depending on the area of application (air, sound, radio communications etc.). The interesting part is that despite the differences, they may sometimes be used interchangeably even within a single application area. Hence, it is beneficial to define these terms within the scope of the present work.

Radio waves are a type of electromagnetic radiation and are a thus a part of the electromagnetic spectrum. They form the the basis of most long-distance human communications. By definition, radio waves are ‘emissions’ from a source (or transmitter) and can be thought of as means by which energy and information can be transferred to an observer (or receiver). Emissions can be very simply classified as naturally occurring or man-made. The ITU radio regulations define interference as the "effect of unwanted energy due to emissions, radiations or inductions manifested by any performance degradation, misinterpretation or loss of information, that could be extracted in the absence of the unwanted energy" [160]. Thus, interference can be thought of as an unwanted signal present at the receiver end of a communications system. Interference is a physical measure of the disturbed signal relative to the original signal sent to the receiver. It can be caused by several sources including the source itself. Interference is also often caused by a combination of known or unknown sources within the communication path. The cumulative emissions caused by each individual source (known or unknown) that become a part of the intended communication signal are ‘noise’ or pollution. It is difficult (and sometimes not entirely possible) to quantify the noise caused by unknown or spurious sources. However, the noise (or emissions) caused by other competing sources in the communication path, while not entirely a linear quantity (i.e. an exact proportion to the number of similar devices), is quantifiable. This is considered as noise in the present work. The details of what constitutes noise and how is it physically quantified is detailed in this section.

3.5.1 Emissions trading in radio communications

Radio communications are similar in this respect. Any type of radio communication activity inevitably leads to "polluting" some frequency bands by sending radio waves through them, rendering them unusable for other potential users.

Unlike air pollution however interference management goals in spectrum are complex and harder to define. For instance, the spectrum auctions have clearly indicated that revenue maximisation is one of the goals. However, spectrum scarcity, especially in view of higher and faster data bandwidth requirement also indicates that goals like higher utilisation i.e. efficiency and throughput capacity are equally important. As different bands are useful for different purposes, spectrum occupancy and assignment goals also vary according to the frequency. Finally, the urban, rural and highways environments offer their own set of goal sets – capacity being the foremost goal for urban areas, while maximum coverage at least cost are important for rural areas and highways. Which such disparate goals, the right-based measure becomes a more logical option for spectrum management.

Also as Weiss states [161], rights-based measure has been found to be more efficient, as it is a market-based policy and hence is a better way to determine the real demand and adjust the prices accordingly. Weiss's proposal [161] involves treating interference rights as an explicit permission to degrade a resource. The normal scenario here means that the frequency bands are pure and available for any signalling purposes. Once a user employs the channel for sending information the band (and nearby bands to some extent) have a higher level of noise, rendering them somewhat unsuitable for use by other interested parties. The interference rights described as such are the exact way in which spectrum is employed to send information. However, the method has to overcome some key constraints in order to be practically applicable to real systems.

Analogous to air pollution, radio communications also produces direct and indirect emissions.

- Direct emissions: Produced when one or a group of transceivers communicate within a cell region (discussed above)

- Indirect emissions: In the Internet of things (IoT) world, much of the focus is on providing services in the form of apps. These apps essentially transfer information to and from the user device (mobile phones or tablets). The transfer of information occurs over wireless channels (i.e. emissions). These can be classified as indirect emissions because, similar to indirect air pollution emissions in Figure 3.3, these emissions are difficult to quantify.

Emissions trading in radio communications takes the idea a little bit further by proposing that the realistic way in which multiple radio technologies can simultaneously operate in a common space is by assigning an allowable and measurable interference cap on each operating transmitter. In a practical sense this means each operator is assigned an interference cap for a set of transmitters operating in a geographical region-frequency band. Based on the technologies used in that and neighbouring frequency-bands and geographical areas, a maximum interference cap can be set for the particular region-time-band combination.

3.5.2 Arguments against using interference as the trading unit

Interference is commonly used as a substitute for emissions in existing work that modifies the concept for carbon dioxide into the atmosphere. Weiss's papers [161, 162] left the question of possible interference parameters up to future research. Some parameters suggested are – interference temperature limit, SINR, interference threshold, and power density. Any of these parameters can logically be a measure for "pollution" within a frequency band. However, spectrum management is more complex than air pollution, because the air pollutants themselves are physical elements and compounds that can be measured. In contrast, RF spectrum pollutants are more complex because of the following reasons:

- Noise is a necessary evil in radio communications as all signals that are not a part of information are noise. Noise is often considered to be analogous to pollution in the air.
- In addition, noise naturally occurs in nature as a result of the many random processes occurring at any given time (unidentified or spurious sources). This noise level changes according to location and time of measurement.
- Noise is not a physically absolute parameter or element like pollutants in air pollution. Noise is relative to the signal being recovered and it is usually calculated by trying to calculate the impact of physical processes that modify the transmitted signal. Several effects need to be considered and hence the noise itself depends on the end use and the quality of the signal desired.

This is the key reason the interference temperature limit was abandoned, as it was too complex to measure accurately for different trading scenarios. Other noise or interference measures suffer the same issues.

Following are the conclusions and proposals based on a review of the existing works:

- All types of noise and interference parameters are essentially the effect of a single variable – transmission power or power density. Interference temperature and threshold are managed by controlling power, and so is the SINR of a channel. Additionally, power related individual parameters are the versions of the parameter that would be technology-frequency-application neutral and one that is relatively easier to quantify. Hence, transmission power (as a measure of noise from sources other than intended), and not interference measure, should be the emission parameter.
- While transmission power is easier to determine than interference, it is effective only when it can be traded practically across disparate technologies. For instance, this

parameter can be used directly to determine additional capacity when overlay and interweave techniques are used. However, in underlay technologies where the power is distributed over a wider bandwidth so as not to exceed the noise floor, power density is not a sufficient parameter that can be used as a physical trading measure. Hence, it would be more logical to include another related parameter to account for spread or noise, in order to account for below threshold wideband noise techniques. This parameter is taken to be the bandwidth of the channel over which power is spread.

3.6 Emission rights in wireless spectrum

Equation 3.1 is the basis of developing spectrum rights. The equation gives the spectrum price, P – price of spectrum used per channel or population – whichever way the equation is defined. In this work, the price is set as the amount of spectrum 'used' (or occupied), converting ownership/property rights to usage rights. Emissions rights, discussed in Section 3.5, are used as the measure of usage of particular frequency bands.

The overall usage/occupied volume variable V is replaced by a *basic trading unit (BTU)*, representing the total volume of emissions rights used by an operator. The Equation 3.1 coverts to:

$$P = \frac{BTU}{M} \times \frac{K_f K_s}{K_m} \times C_s \times K_p \quad (3.2)$$

The basic trading unit for emission rights for wireless spectrum is proposed as a two-dimensional quantity comprising of: Power p and Bandwidth b. Thus, emission rights of an operator in the spectrum market in a particular frequency band can be given as below:

$$BTU = p \times b \quad (3.3)$$

This can also be considered as the spread of power (noise) across a bandwidth to achieve a desired communication goal. The power-bandwidth spread is inherently dependent on the technology selected to achieve the communications goal. In case of traditional narrowband technologies, the transmitted power is large but it is spread over a relatively smaller bandwidth. In contrast, in case of ultrawideband technologies, the transmitted power is very small (in the order of 1 mW), but it is spread over a larger bandwidth. This is shown in the Figure 3.4, which shows three technologies - narrowband, broadband and ultrawideband technologies, in terms of power spread.

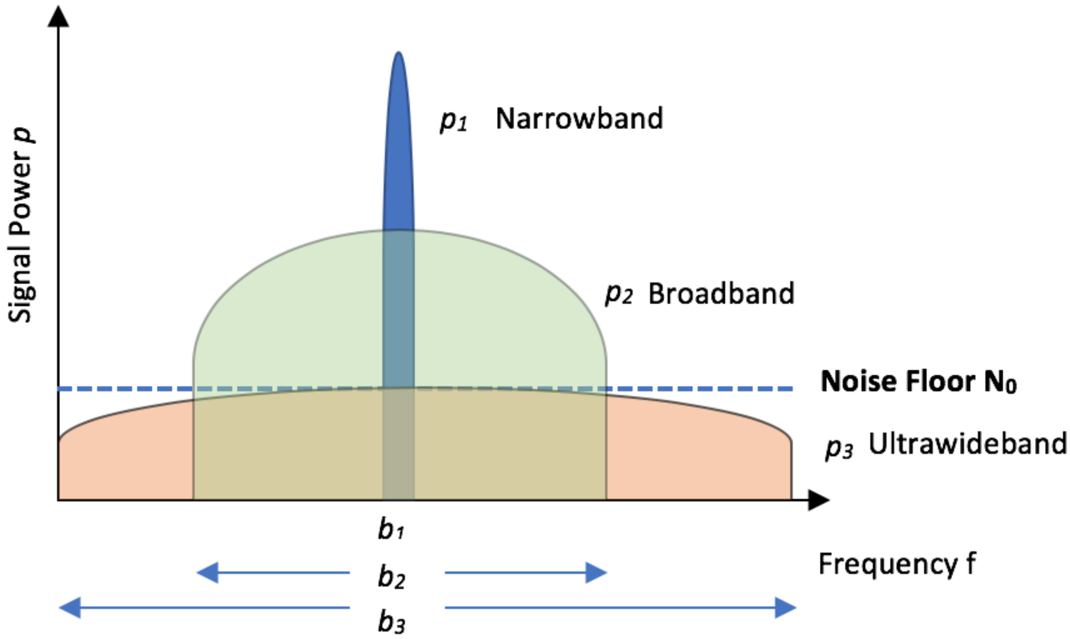

Fig. 3.4 Power spectral density for different technologies (Image adapted from [163])

For an operator, power transmission is not uniform across all the bands involved. Reasons such as power bleed into adjacent bands (reference), contiguous and non-contiguous carrier aggregation (in case of LTE) mean that the summative effect should also be considered. In the current spectrum assignment landscape, this is done by separating adjacent assigned frequencies by a guard band. However, for a scarce resource like spectrum, locking out bands in entirety is essentially wasting the resource. The solution is to create a spectrum profile that would detail the amount of power transmitted in different bands. This information would help the bands to be used by alternative technologies. Thus the Equation 3.3 should be modified to include a summation of the power over the bandwidths over which the power is transmitted as shown below:

$$BTU = \sum_{i=1}^{n} p_i \times b_i \tag{3.4}$$

For instance, in the case of LTE carrier aggregation bandwidth can be acquired in the same bands or in different bands. Even when the bandwidth acquired for the next stage is in the same band, the assignment might not be contiguous. This is shown in parts (a), (b) and (c) of Figure 3.5 above. For such cases, if the operator is able to acquire permits to transmit p_1, p_2, p_3 in the bandwidths b_1, b_2, and b_3 respectively (shown by the green, orange and

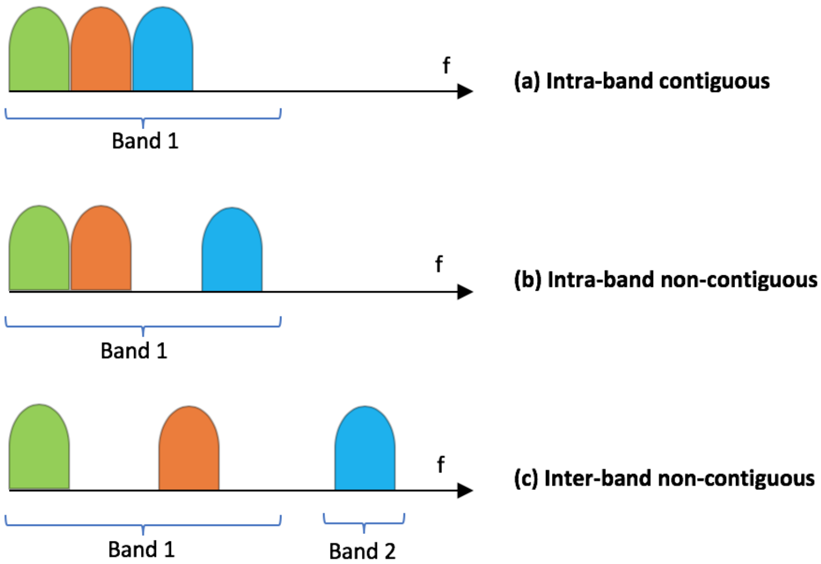

Fig. 3.5 Carrier aggregation options in LTE (adapted from 3GPP website [164]

blue bands in the Figure 3.5), then the total emission footprint (i.e. total trading units) for the operator would be given as below:

$$BTU = p_1 \times b_1 + p_2 \times b_2 + p_3 \times b_3 \tag{3.5}$$

The total value of the spectrum is now be expressed by modifying Equation 3.2.

$$P = \frac{\sum_{i=1}^{n}(p_i \times b_i)}{M} \times \frac{K_f K_s}{K_m} \times C_s \times K_p \tag{3.6}$$

Equation 3.6 is from the perspective of the regulators, who can use it to set the prices or licensing regimes for different frequency bands. These aspects would be discussed more in section 3.7.

From the perspective of buyers, the Equation 3.6 can be rewritten as:

$$P = \frac{\sum_{i=1}^{n}(p_i \times b_i)}{MK_m} \times TASF \times C_s \tag{3.7}$$

Following are the four coefficients in Equation 3.6.

K_m= Coefficient reflecting social benefit of radio system

K_f = Coefficient reflecting specific characteristics of range used

K_s= Coefficient taking into account the region of the radio station installation

K_p = Coefficient reflecting the level of spectrum access demand in the band in question

Three of these coefficients, K_f, K_s, and K_p, can be clubbed together because they are specific to a particular application and thus vary for different operators. These can replaced by a common factor $TASF$ i.e. Technical application suitability factor, as a function of these individual factors.

$$TASF = f(K_f, K_s, K_p) \tag{3.8}$$

The next points of discussion relate to the parameters M (representing pollution) and $TASF$, presented in the sub-sections 3.6.1 and 3.6.2 respectively.

3.6.1 Population density in IoT age

Mobile networks are designed around the number of end user devices within a given region. This is the parameter M in the Equation 3.6. M is equivalent to the population density or population in a unit region area. Until recently, the population and device numbers were used interchangeably to express the demand within a region.

$$Population\ density\ M = Device\ density \tag{3.9}$$

Mobile device penetration rates are expressed as a percentage of the population within a region. Until recently this percentage directly reflected the demand and adoption rates of cellular services within a region. The device penetration rates in developed countries then could be expected to be higher than 100% as certain classes of customers, could own more than one cellular device. Cellular device penetration rates directly translate into mobile network infrastructure requirements, and data rates (in the IP age). Better technology i.e. newer generations, arguably require better data rates because of the number of people using the technology and the newer applications expecting a set of streaming requirements. The expectation was that when cellular device rates reached a saturation point, the future technology would focus on improving data rates and seamless interconnectivity[1].

The landscape changed with the introduction machine-to-machine (M2M), machine-type communications (MTC) and IoT devices. This has shifted the requirements and expectation

[1]While there were other devices used in the households/workplace that required connectivity to the internet – mainly computers and laptops – these devices primarily used wired broadband combined with wi-fi to satisfy the demand. Mobile broadband became a requirement when smartphones were introduced in 2007. In fact ITU's 4G system requirements laid the foundation for mobile broadband service demands.

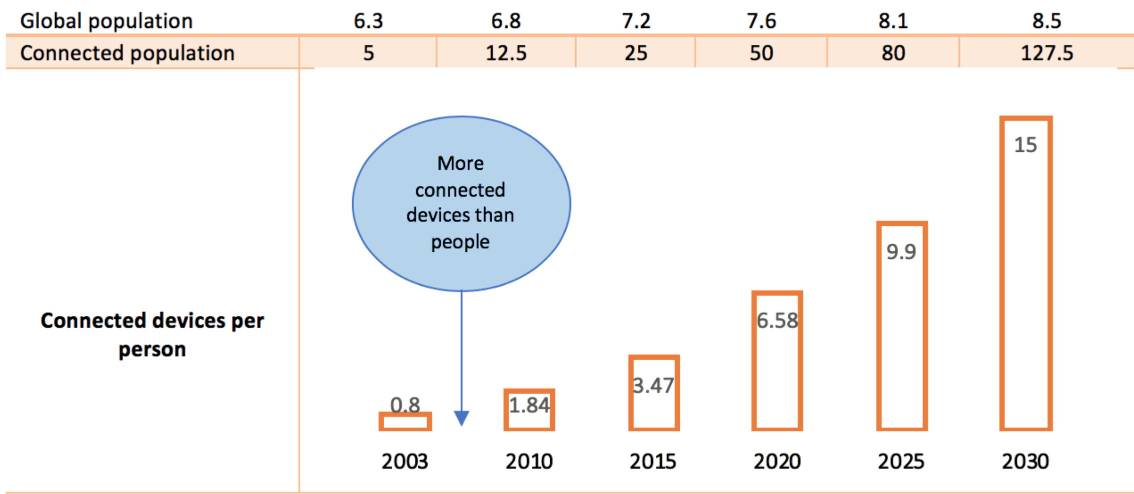

Fig. 3.6 Connected devices per person (chart data from [165, 166])

from mobile networks. Seamless connectivity is no longer limited to remaining connected via smartphones, regardless of the location. It has extended to increased use of additional devices such as wearables, smart meters, smart parking and home automation devices and their interconnectivity to the members of a household at all times. This means that the number of connected devices in household has now exploded. The number of devices per person was 0.8 in 2003 [165]. This number exceeded the global population between 2005-2007 and is expected to increase to 15 devices per person by 2020 [166]. The statistics are taken from Statista and IoT analytics and combined with the global population data; the results are shown in the Figure 3.6[2].

3.6.2 Types of cellular devices IoT age

Because the number of users massively exceeds the population, population density within a region can no longer be taken as a proxy for device density, even as an approximation.

$$Population\ density\ M \neq Device\ density \tag{3.10}$$

[2] The numbers clearly show that the smartphone or other similar device penetration ratios are no longer relevant in current times. More than that, the ceiling for penetration rates is also very high. This automatically means a difference when assessing the mobile spectrum costs. The penetration rates and data demand guide the prices per pop, which in turn is dependent on the cost of infrastructure.

At the same time, because a large proportion of the newer devices are IoT and are much different from the traditional mobile devices, the device density is also not a simple multiple of the population density.

$$Population\ density\ M \neq n \times Device\ density \tag{3.11}$$

When calculating device density, the type of devices must also be taken into account. For this purpose, mobile communication devices have been divided into two types – primary devices and secondary devices. This classification is different from the standard division proposed for the mobile networks in dynamic access systems. In most research papers, primary devices refers to network devices that have the first access to the network, while secondary devices use the unused bandwidth either by lawful purchase/sharing agreements or via opportunistic access. Both primary and secondary devices are generally similar in terms of functionality and throughput features. In contrast, in this work, the type of devices refers to the functionality of devices themselves. Unlike the standard dynamic access classification systems, these devices don't necessarily compete with each other for resources. While, secondary devices sometimes make use of the network resources intended for the primary devices, this is either done by way of cooperation (often, the owners of both services are same) or the overall noise levels generated by the secondary devices is lower than the threshold that would cause interference to normal operation of primary devices. It must be noted that the threshold is a variable and is dependent on factors such as the region of operation (urban, semi-urban, rural etc.), the time of operation and the total number of active primary devices. A classification of the devices is given in the Figure 3.7. The technologies mentioned in Figure 3.7 are mostly narrowband, however, the secondary devices can also make use of existing LTE technology or ultra wideband technology to provide similar services. Information used in the Figure 3.7 has been taken from ITU training documents [167].

- Primary devices – These devices are the future improved versions of the traditional mobile phones, e.g. smartphones and tablet devices. The expectation from primary devices go beyond the basic mobile phone requirements of good voice quality and reliable text message delivery. Primary devices require also require high data rates and low latency. This is because primary devices are multifunctional and some of the functions like streaming are data intensive with very low latency expectations. For instance, as per ITU a latency of less than 10 ms is a requirement for an acceptable broadband experience. The target peak downlink rate is 1.5 Gbit/100 MHz/s. The target peak uplink rate is 675 Mbits/100 MHz. The throughput is 20 Mbps to 100

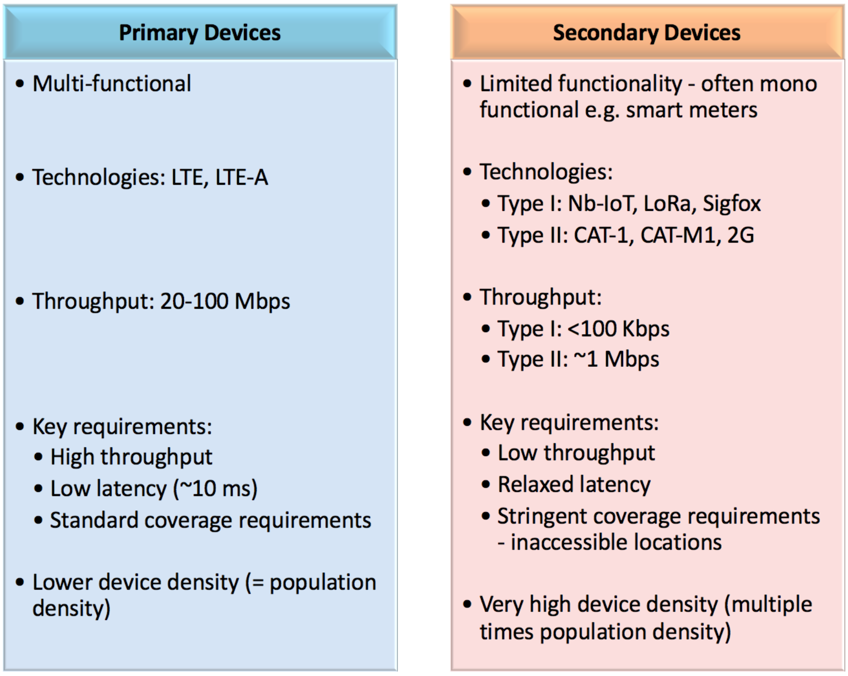

Fig. 3.7 Classification of cellular devices

Mbps [168]. Additional requirements are good coverage and seamless connectivity. Because of high functionality, these devices are more expensive and hence there are limited number of the devices – usually one or two per person in a household.

- Secondary devices – With the advent of mobile to mobile (M2M), machine type communications (MTC) and IoT devices in general have given rise to a secondary type of device. These devices do not have high-end functionality as the primary devices. In many cases, the devices are intended for a single type of operation. Because of the proliferation of *smart* devices, the number of secondary devices has exploded. Any electronic device used in the household has the capability of being turned into a smart device. Examples of consumer devices include smart meters, smart toys, wearables, smart appliances etc. In an industrial setting include smart factory machinery would be one of the types of secondary devices, in additional to the standard smart office devices. The secondary devices are characterised by low-data rates and low latency requirements. In addition, the devices also have low throughput. However, the devices have stringent coverage requirements. Often such devices are located in inaccessible places like basements, which are traditionally seen as cellular blackspots. For instance, technologies such as Long Range (LoRa) and Narrowband Internet of Things (NB-IoT) that are intended to be used for devices such as smart parking, smart agriculture, asset tracking, smart sensors etc. have a low throughput of <100 Kpbs. Technologies such as 2G/3G/Cat-1/Cat-M1 that are used for IoT backhaul, wearables etc. have a throughput of 1 Mbps. The technologies however provide a better coverage [167].

Thus for a unit area, the total number of devices with a unit area, i.e. the device density, is a sum of the primary and secondary devices within the area.

$$Device\ density\ M = Primary\ devices + secondary\ devices \tag{3.12}$$

From the discussion it can be seen secondary devices use only a fraction of the resources as compared to the primary devices and have much lower throughput requirements. However, they are much more numerous than the primary devices and have stringent coverage needs. This means the resources required would not be a direct factor of the throughput, they may also need target localised coverage resources.

However, to convert this into the effective number of connections (equivalent to the population count) M, the overall impact of the devices should be considered. This is done by introducing a modification factor η to account for the effect of secondary devices in the network.

$$Device\ density\ M = Primary\_devices + \eta \times secondary\_devices \tag{3.13}$$

The modification factor is dependent upon the percentage of secondary device data rates with respect to the primary device data rates and the percentage of network resources used by secondary devices with respect to the resources used by the primary devices.

$$\eta = Network\_usage\_proportion \times data\_rate\_proportion \tag{3.14}$$

If there are different technologies used for secondary devices in a region, each will have different modification factors. For instance, if in a network there are devices using Type - I technology like Nb-IoT and devices using Type - II technology like Cat-1, their data rates are different as are the amount of resources they use. Hence, the modification factors would be different too.

$$Total\_devices = Primary\_devices + \eta_1 \times D_1 + \eta_2 \times D_2 \tag{3.15}$$

η_1 = the effective impact caused by D_1 Nb-IoT devices

η_2 = the effective impact caused by D_2 Cat-1 devices

3.6.3 Technical application suitability factor

In a perfect resource world scenario, RF spectrum would have the same characteristics regardless of the frequency band. When each seller offers the spectrum for sale, there would be an inherent knowledge that the spectrum offered would perfectly satisfy the demand for all buyers in the market. The differences in demand and supply are on quantity of the resource in question, not the actual characteristics of the resource itself. However, the propagation characteristics of spectrum are very different across different frequency bands. The frequency of a radio wave determines its characteristics such as: the distance it can travel (longer wavelengths travel further, but require a larger antenna), penetration through trees or into buildings, and the cost of equipment (directly proportional to frequency) [84]. Different services need frequencies (wavelengths) with different characteristics. Thus RF spectrum is broadly segmented on the basis application usage (dependent on transmission characteristics) as shown in the Figure 3.8 below.

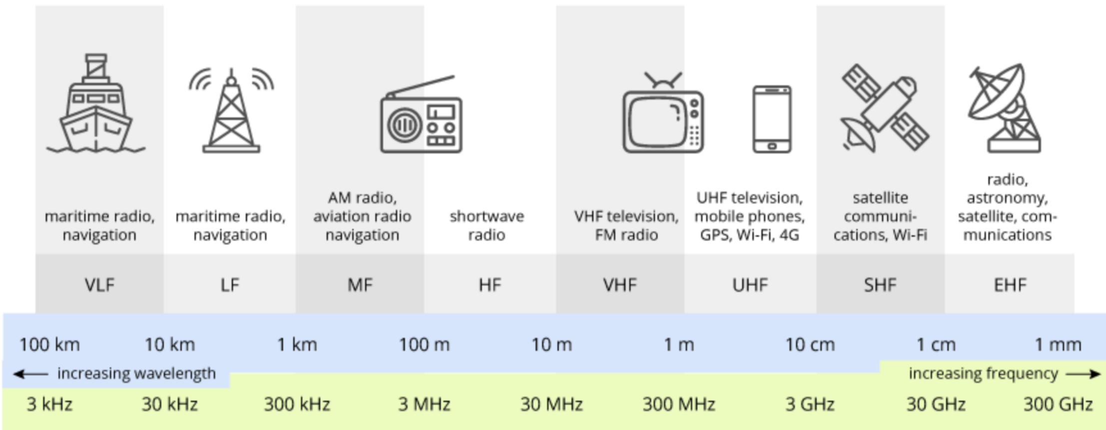

Fig. 3.8 RF spectrum [169]

In 2012, Weiss [170] introduced the idea of "fungibility" – items that were perfectly interchangeable with each other – to RF spectrum for ascertaining their comparative usability to mobile network operators. From the discussion above, it is obvious that all bands of RF spectrum are not necessarily "fungible" with other bands. Hence, available bands have to be assessed based on their suitability for an application. Weiss's work is focused on determining the fungibility ratio based on the physical characteristics of the system. This score is actually equivalent to the coefficient K_f in Equation 3.8 and Equation 3.8, which is a coefficient reflecting specific characteristics of the frequency band. Fungibility score can be used to determine the extent to which an available band meets the requirements of a spectrum buyer. In Chapter 5, other aspects of available spectrum are introduced, that also have to be taken into account by spectrum buyers to determine their suitability, in a dynamic spectrum access scenario. In addition to fungibility, operators must also take into account the cost they wish to spend acquiring the spectrum and the cost of infrastructure around it.

Even if the available spectrum is suitable for the operator requirements, there is a limit to which the operator might be willing to pay. Conversely, if a frequency band does not satisfy the requirements completely, operators may still be willing to acquire the bandwidth to satisfy part of their requirements. Thus, the coefficient reflecting the level of spectrum access demand in Equation 3.8 and Equation 3.8, K_p can be used to determine the cost desirability factor C_A.

$$C_A \propto K_p \tag{3.16}$$

In the same way, the number of base stations is directly related to the frequency bands and the region in which the radio network is deployed. Hence, the cost factor for setting up the infrastructure is directly proportional to the coefficient reflecting specific characteristics of range K_f and the coefficient that takes into account the region of the radio station installation K_s, given in in equations 3.2 and 3.8.

$$C_I \propto (K_f \times K_s) \tag{3.17}$$

$TASF$ can now be reduced to a function of the two cost factors:

$$TASF\_score = f\ (C_A, C_I) \tag{3.18}$$

Where:

C_A = Cost desirability factor of acquiring the band in the market. This is also represented on a 0 to 1 scale, 1 representing the condition where the band is available at the desired cost. The factor approaches 0 as the cost becomes higher. In addition to spectrum demand, C_A also depends on the period of availability, which is relevant when spectrum channels can be acquired for shorter periods of time. These factors are further discussed in Chapter 5.

C_I = Cost factor of setting up the infrastructure around the available frequency. This is also represented on a 0 to 1 scale, 1 representing the cost of setting up the infrastructure using the ideal frequency band for the application. The factor approaches 0 as the cost for setting up the infrastructure decreases.

3.6.4 Spectrum - licensed or unlicensed?

The debate around spectrum licensing is one of the most enduring and relevant in the telecommunications domain. The decision has potential impact on access to a multi-billion dollar resource, the use of which has a profound impact on every aspect of the modern society. The task of the regulator is to select an assignment mechanism from the three available models, summarised by Hazlett as below [171]:

- Command-and-control – The frequency bands under command-and-control usage are in high demand and the licenses to operate are secured via competitive bidding process.
- Commons – The frequency bands under commons use are shared by multiple commercial parties e.g. class licenses for backhaul network.
- Exclusive use: The frequency bands under exclusive usage, for instance those occupied by the defence authorities in various countries, have complete ownership rights that are theoretically transferable. Examples of such licences in commercial domain are in existence in Guatemala and El Salvador.

The issue with this is that this taxonomy [171] confuses access regimes with property regimes. The former discusses how consumers/producers use the resources, while the latter is how to actually some market organisations are chosen and others excluded, not by competitive markets but by bureaucratic decisions. For instance, unlicensed bands are not "commons", they have been administratively assigned to operate within tight frequency and power limits. The decision on which type of regime fits which bands is made at the bureaucratic level. As seen in Chapter 1, many of these decisions were either as a reactive measure to certain events (either a disaster or lawsuits or widespread corruption) or were taken under influence from other countries (large monies generated from auctioning spectrum). Resource management using competitive market forces would be more efficient, as consumer demand could be taken as the marker for the type of property regime that would best suit a particular frequency band within a given region.

The emission rights model proposed in the previous sections can be used for determining the resource management for particular frequency bands in a region. To recap, for a frequency band spectrum price based on emission can be calculated using Equation 3.6. If the combined perceived value of the spectrum band $Value_p$ within a given region – a combination of power noise spread in the band, number of users and operator demand – falls below a threshold, then the band is contention free and the interested buyer can theoretically access the spectrum without paying license fees (apart from minimal administrative fee). If there is contention in the band, then market price is determined based on the demand and perceived value among buyers.

$$Value_P = \begin{cases} No\ spectrum\ license\ fee\ applies, & \text{if } Value_P < V_{th} \\ Market\ price & \text{if } Value_P \geq V_{th} \end{cases} \tag{3.19}$$

Where: V_{th} = Threshold spectrum value. The decision of threshold value is based upon the current band usage

3.7 Spectrum acquisition process

Spectrum rights can be defined explicitly based on the parameters discussed above and the usage levels of the individual operators. This section provides a brief overview of how this process works for the operators.

Sellers: Sellers i.e. the original owners of the spectrum publish the available rights in the market. It must be noted that generally speaking all the spectrum belongs to the public or the government. Spectrum rights are only offered as a lease for a fixed term, though in countries like Guatemala and El Salvador mobile operators actually hold the full ownership rights (these rights also expire after a given period of time). Different type of spectrum ownership rights have been examined by researchers [5, 131]. Howeve, the proposed BYOS framework currently only focuses on the time-limited aspect of the rights and it is assumed that these rights are transferable (at least over a short-term basis). Spectrum lots are created based on the rights published in the market. A spectrum lot comprises of constraints such as maximum transmission level, maximum allowable interference (emission limits) in adjacent bands etc. An example of a spectrum lot using parameters discussed earlier, is shown in Figure 3.9.

Frequency band
Bandwidth available (contiguous)
Max. allowable emission limits
Availability time period

Fig. 3.9 Sample spectrum lot – demand profile

Emission limits may be given directly or indirectly in terms of minimum QoS or throughput expectations in the presence of secondary users.

Buyers: In response to the published available rights, buyers have the option to bid. Sellers can choose the best available option based from the bids. For instance in the 3.10 below seller chooses the highest bid among the four bids presented for the spectrum lot advertised.

	Bid 1	Bid 2	Bid 3 (highest)	Bid 4
Prices	70 units	65 units	80 units	75 units

Fig. 3.10 Simple price-bids for an available spectrum lot

Alternatively, in response to the advertised lot, buyers can present a demand profile providing their emission requirements, required time of usage and price. In this case, sellers can choose to accept a demand profile based on whichever demand-price option that gives them the best return. The choice of how to determine a winner is left up to sellers, so there is no need to formulate a common winner determination algorithm. For instance, in case the buyers publish a demand profile that asks for more in terms of emissions or time than advertised and is ready to pay for the privilege, sellers are free to make the decision to reorganise their usage and sell additional capacity to the buyers. An example is shown in Figure 3.11 below, where the seller accept the bid from the buyer, agreeing to the demand for more time

Bid 1	Bid 2	Bid 3	Bid 4
Price 1	Price 2	Price 3	Price 4
Demand profile 1 (extra time)	Demand profile 2 (more emissions)	Highest for existing lot	Demand profile 3 (time + emissions)

Fig. 3.11 Alternative bidding options in response to an available spectrum lot

3.8 Emission rights in the BYOS framework

In this section emission rights are applied to the BYOS framework. As seen in Chapter 2, the framework allows three levels of access based on period of acquisition. The framework follows hierarchical spectrum assignment – mobile operators at the higher levels are allowed to own spectrum for longer periods, allowing them to develop a stable and financially viable mobile network. Operators purchase spectrum required for satisfying peak data demand in the market competing with all other participants. The discussion below shows how noise can be used by operators at different levels to express their demands.

- Long-term access – This type of access is reserved for incumbent mobile network operators. At this point, the operators can acquire spectrum that would be necessary for signalling. For instance, in UMTS architecture, part of the downlink power assigned for the common channels because these signals are operated independently of the traffic channels. The amount of power assigned to power channel affects synchronisation time, channel estimation accuracy and the reception quality of the broadcast channel. At the same time, it is well known that the power assigned is part of the power that could have been assigned to the traffic channels. As common channels are a necessary part of a mobile operating infrastructure, emissions necessary for signalling purposes are assigned as part of the licenses for incumbent mobile operators. This would allow the operators to set up the network without worrying about acquiring the spectrum – as part of initial network roll out process.

- Medium-term access – Medium term access is similar to the way spectrum assignment works currently. Operators (whether incumbent or older MVNOs or new operators) acquire spectrum for a relatively shorter period of time. The logic behind this is that the operators can have agreements to access the mobile core network from incumbent operators and build-up their capacities over the existing network. At this point, power can be acquired to build the whole network based on standard speculative processes. The spectrum can be acquired or shed as required based on real-time capacity assessments. The time frame for assignment is shorter, though just like many countries are doing now – the assignment period can be rolled over to the next period (the UK example)– if there is no demand or if the current operator has the best-established network to provide the services. This is left to the discretion of individual countries.

- Short-term access – Like most dynamic spectrum assignment schemes, short-term access in our framework does not mean spectrum acquisition in real-time. This aspect of our framework actually brings in the idea of quasi-static ownership of spectrum. At this time spectrum can be assigned to all types of users – incumbent or new operators. Spectrum is traded depending on availability only. Each of the operator gets pollution permits for a fixed period. Unlike the long- and medium-term assignment, users at this stage are not allowed to extend the period in an ad-hoc manner and must participate in the market for the next period to assign spectrum. The period does not roll-over and ends when the shortest period of medium-term assignment expires. Multiple users are allowed to spread noise in the same band, until the overall permitted noise exceeds a pre-decided limit.

The noise limits for every band have been studied in detail and this information is more than sufficient for creating an database of users. The discussion of the noise levels and database is discussed in chapters 4 and 6 respectively. Spectrum usage needs coordination, which is the reason the auction/trading is not conducted in real-time. There is a look-ahead period that allows base stations to plan switching over process. The operators also get a chance to coordinate the available spectrum with the existing spectrum to plan for the market.

3.9 Summary

In this section, the spectrum assignment process using emission rights was discussed. The chapter presented the uniqueness of the spectrum "resource" – more accurately the wireless medium. The discussion on the similarity to a multi-lane highway provided insights into assignment of usage, based on density and quality of usage. The emission parameter is the best suited as the trading unit, because it defines the demand in terms of signalling that can be used to calculate interference based on proximity (both nearby bands and physically nearby users). The trading unit was then refined by adding additional parameters that expressed demand, but are application-agnostic. Finally the rights were applied into the BYOS framework to show how emissions-based parameter can be used by operators at different levels to express their demands. The parameter can be used over different time scales and is operator-application-band agnostic, which makes the framework flexible. Different types of operators entering the market based on individual demand is clearly a situation requiring dynamic regulation. The mechanism to achieve this is discussed in Chapter 4.

Chapter 4

Manage competition using tokens

This chapter extends the technical discussion of this thesis to include the economic concept of competition management. The issues related to existing competition management schemes in spectrum management are presented first. A novel mechanism of competition management (token) is then introduced, followed by a theoretical background of the concept. Various use case scenarios covering the different ways in which tokens can be used to manage competition in the framework are then presented.

4.1 Competition management

Competition management is one of the key issues in spectrum regulation and management. The primary reason auctions were introduced to assign, and price licenses was because it was the fairest means available to distribute the resource to parties that most desired it. It is no coincidence that assignment of licensing to private for-profit companies has directly led to the rapid development of wireless telecommunications globally [172]. The technology growth has been similarly fast, as has been the adoption rate. In less than half a century the number of users has increased from a minor fraction of the population (in the 1980s) to multiple times the entire global population (post 2010).

Despite this, since their very inception, spectrum auctions have proven to be less than economically efficient, i.e. applying the resource to its best use. Some of the issues, discussed earlier, include what "efficiency" means and how to quantify this in terms of economic value. In case of spectrum – a valuable, scarce, and necessary resource – multiple definitions of efficiency have to be balanced. As it is a valuable resource, also a public resource, it is the duty of the regulator (in this case the government who is also the seller) to ensure that the resource is assigned to the buyer who values it the most – the definition of allocative efficiency [173]. As spectrum is a scarce resource and also necessary, it is the duty of the regulator to ensure that the resources are assigned to the buyers who are able to make use of the spectrum to provide the best possible service to their customers i.e. the public. By nature of the resource, technical efficiency [173] is also an aspect that needs to be considered, which essentially underlines the "degree of fungibility" aspect. Resource valuation between the buyers varies depending on transmission characteristics of the available spectrum block and the spectrum already owned by the buyers (i.e. the contiguity aspect).

Additionally, the value any bidder attaches to a spectrum license (especially on a long-term speculative basis), is different from the social concept of economic efficiency. From a pure competition viewpoint, it is fair to attach a value to the spectrum that also includes the cost of keeping the resource away from the competition. However, when this leads to unsold spectrum lots or drives the price high enough to make the competition go bankrupt (again leading to unused spectrum), the issue becomes more than mere anti-competitive practice.

This happens because spectrum is a scarce resource and license acquisition is the only way to acquire access to it. In addition, the opportunities acquiring licenses are also very occasional ? not even failed auctions would immediately grant the right to access this resource to another interested party. There would have to be a separate auction that may take years to organise. Hence, any potential chances to acquire spectrum is not exactly looked upon from the point of economic efficiency, several other factors come into play as well. For instance, spectrum may also be may acquired in anticipation of the success of speculative technologies. A classic case of 'warehousing' in this context is when Qualcomm – via its subsidiary 3G Investments Pty Ltd. – acquired licenses for launching its CDMA-2000 services in Australia in the 2001 auctions [174]. The spectrum was eventually sold to Optus following years of waiting for the right price - a clear case of warehousing of scarce resource [175].

The wireless telecommunication sector is also infrastructure dependent. That is, any company purchasing spectrum license at a high cost also has to possess sufficient capital for deployment. This includes infrastructure costs as well as operational expenses on a long-term basis. Thus, the competition is naturally skewed towards larger organisations. When the telecommunications sector was liberalised, the larger operator was the government. The secondary license holders in most countries were given major infrastructure-related concessions, ensuring more fair competition with the incumbent operator. The third or fourth operator concept began in Europe and usually comprised the primary or secondary license holders from other countries in partnership with local operators. These operators also subsequently became the third (and other) license holders in other countries subsequently, as they had sufficient capital outlay and experience to run mobile networks.

4.1.1 Competition measures introduced by the government

The conflicting aspects of evaluating efficient spectrum usage have made the assignment process highly prescriptive and lengthy. This discussion shows that granting spectrum-related concessions during auctions is not sufficient to sustain competition among wireless network operators. Governments have introduced several means to jumpstart competitions such as:

- Spectrum caps – Limits on the quantity of spectrum that can be held by an operator [176]. As a means to manage monopoly, this is an effective mechanism. However, as telecommunications sector is a natural oligopoly, caps cannot be the only means to manage competition.

- Spectrum set-asides – Reserving a particular spectrum lot or amount of spectrum for particular types of competitors, often new-entrants [176]. These haven't been successful as many new entrants have either merged with existing operators or have exited the market e.g. through bankruptcy. The reason is the infrastructure-intensive nature of operators, which means reserving lots as a means to reduce entry barriers is simply not sufficient.

- Spectrum floors – They are inverse of spectrum caps and ensure that an operator has a minimum quantity of spectrum necessary to operate a network, provided it has sufficient funds to pay the reserve price [176]. This type of model is good, if spectrum is allotted at a single auction. For progressive assignment, such as the case of Indian 2G spectrum assignment, this can become a hindrance as it leads to too many operators with only the minimum quantity of spectrum

A report by the GSM Association (GSMA) [177] on the issue agrees that merely setting spectrum or even concession prices to new entrants cannot help with boosting competition. Spectrum should be allotted only to the entrants capable of rolling out the network and operate it. However, this automatically means only larger operators are able to enter the market. Our flexible time frame is the first step to ensure that spectrum can be tested for deployment for a shorter period before deciding long-term roll outs. However, as stated above unfair competition practices are a given in this sector and active government intervention actually hinders competitions.

4.1.2 Proposed mechanism for competition management

Based on the information gathered from existing sources (covered in Chapters 1 and 2), following are the desired features expected of a self-regulating framework:

- Automated: Automated mechanism for competition management allows the framework to be automated, which makes the assignment process faster and more efficient
- Immutability: The property of immutability allows the mechanism to provide reliable information on the trades by participants within the framework
- Transparency: The mechanism is transparent to the regulator who can use the information to audit any trade within the framework
- Punitive: The mechanism can be used to regulate the behaviour of participants in the market. Needless to say the power of taking punitive measures within the framework rests only with the regulator.

The above features allow the regulator to be able to trace any trade and regulate the behaviour of participants. This means that the regulator can now take a non-interventionist role in the market. As seen from the discussions in previous chapters, this would be a desirable outcome.

The multi-lane highway analogy discussed in Chapter 3 was the main influence behind the development of the mechanism for competition management presented in this chapter. In the analogy, spectrum is considered as a *multi-lane highway*, so it follows logically that information travelling over the highway would be the *traffic*. Management of traffic essentially means restricting the flow at specific instants of time.

Traffic shaping is also carried out in computer networks to manage, control or reduce overall network traffic. The purpose, in this case, is usually to guarantee performance, improve latency, or increase usable bandwidth. Two key mechanisms for traffic management are traffic policing and traffic shaping that help regulate bandwidth usage by limiting the amount of traffic per usage. Policing limits traffic rates by dropping extra packets; other methods include re-marking or transmitting traffic only if it conforms to a policy. In contrast, shaping involves regulative excessive traffic rates by delaying i.e. buffering traffic. There are several traffic management techniques [178]. One of the more interesting ones involves using "tokens", which is used as a mechanism for managing competition in the proposed framework.

Before describing the use of tokens in the proposed framework, it is prudent to review the concept of tokens within its original context. This is presented in Section 4.2.

4.2 Background – Tokens in network traffic management

4.2.1 Leaky bucket

One of the basic algorithms used for defining data bandwidth and burstiness (measure of variations in data flow rate) is the leaky bucket – named because of the analogy to a bucket leaking at a certain rate. If the flow of the bucket is more than the rate of leakage, the bucket will overflow after some time – depending on the depth of the bucket [178]. Figure 4.1 shows the concept of leaky bucket. Leaky bucket can be used for both traffic policing and traffic shaping purposes.

The leaky bucket can be applied to traffic management in two ways:

1. Leaky bucket as a meter – Leaky bucket represents the net contents of the bucket at a given time.

$$Net\ bucket\ fill\ rate = Inflow\ rate - Outflow\ rate \tag{4.1}$$

If the net rate of filling is maintained so that the bucket does not overflow, this means that the bandwidth and burstiness are at an acceptable rate and won't lead to loss of packets. The counter is independent of the actual traffic flow and does not manage the packets directly in terms of scheduling [179].

2. Leaky bucket as a queue – In this method, the leaky bucket acts as a queue directly controlling the traffic flow. This means that the packets exit in the order of entry (first-come-first-served). This means that the bucket actually controls the rate of inflow and outflow to conform to the required standards, unlike the first method where it just acts as a monitor to be controlled independently [180].

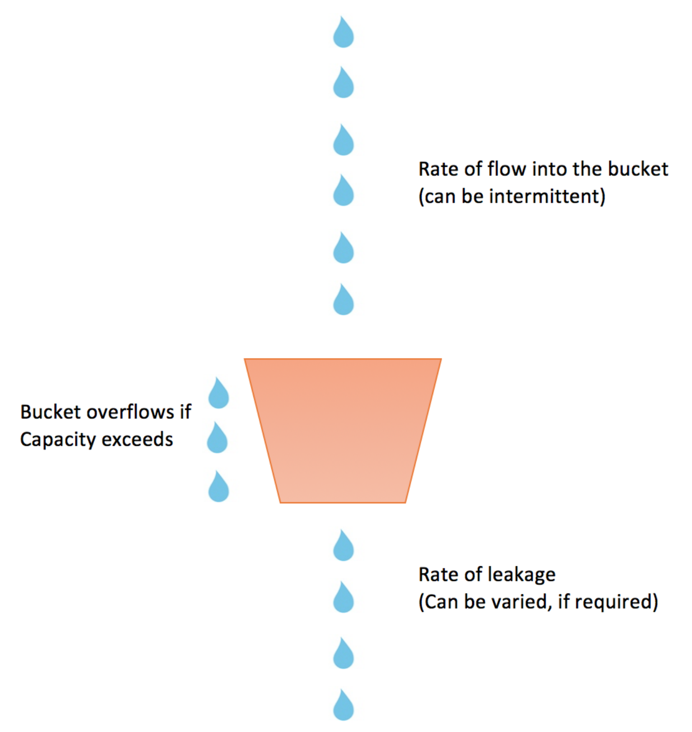

Fig. 4.1 Basic leaky bucket algorithm

Figure 4.2 shows the use of leaky bucket in network traffic scenario. When used as a meter, the regulator would simply release the packets at a given rate and overflow occurs if the storage exceeds capacity. When used as a meter, the regulator would also take care to release the packet in the order in which they entered.

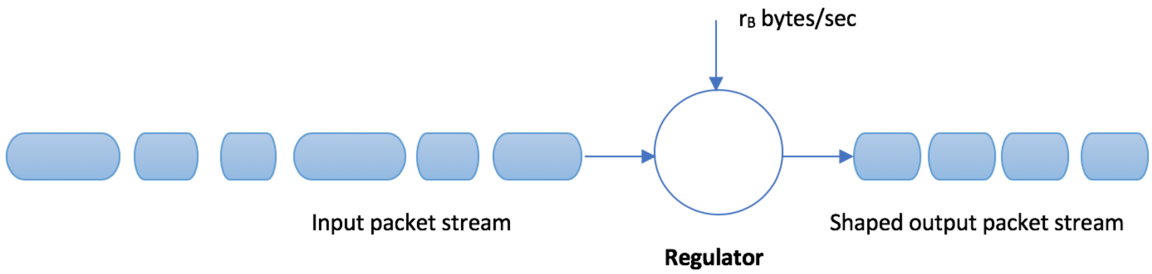

Fig. 4.2 Leaky bucket to manage network traffic [178]

4.2.2 Token bucket

Token bucket is another mechanism to police or shape network traffic. The bucket concept is similar in that there is an inflow and a specified outflow rate, and the bucket has a finite depth or capacity beyond which it will overflow. The key difference is that the bucket is not filled up with packet (or direct traffic), but tokens. Tokens fall into the bucket at the average rate to be policed (or shaped). For instance, in case of the Figure 4.3 about r_T bytes/second is the rate of the output stream. If this was managed using a token bucket method, then tokens would fall at the rate r tokens/second. The token bucket has a capacity limit (or depth) and overflows when the number of tokens exceed the capacity. In general, the depth is a measure of burstiness capacity of the data to be policed, so that no packets are lost. Packets can pass through only when there are enough tokens in the bucket. This means only packets of size r_B bytes are passed or all packets are combined together and passed ahead at the rate of r_B bytes per second [178, 181]. Non-conforming data packets can either be:

1. Dropped altogether

2. Queued for future transmission when there are sufficient tokens in the bucket.

3. Dropped if network is overloaded or else transmitted but marked as non-conforming

Token bucket operation is shown in Figure 4.3.

When multiple parameters in network traffic have to be policed two or more buckets can be used. For instance, in case of managing two parameters a combination of concepts discussed in 4.2.1 and 4.2.2 can be used – two leaky buckets, two token buckets or one leaky and one token bucket. A common example is where both peak rate and burstiness are policed. A leaky bucket can be used to manage peak rate (packets with higher data rates are discarded) and then a token bucket can be used to police burstiness (release packets smoothly at a designated rate) [181]

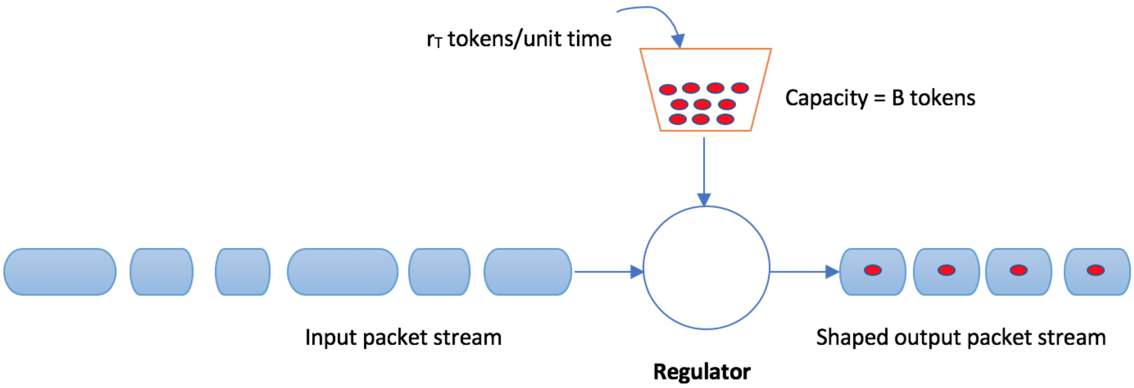

Fig. 4.3 Token bucket to manage network traffic [178]

4.3 Tokens in the proposed framework

In the proposed framework, tokens can be used similar to the discussion in Section 4.2 that will allow automated control of the market. Regulators monitor and control the market, but indirectly by making use of tokens. Figure 4.4 shows how tokens can be used to regulate market behaviour and hence spectrum usage allotment for different users.

The token allotment begins at the start of a short-term assignment period. Recall that a short-term assignment cycle is the longest period of assignment during which short-term rules for spectrum assignment apply. The rules include allowing all types of participants into the trading system for this period, a quasi-dynamic model of assignment (for short periods down to 1 hour) and no ownership rollover post expiry.

As shown in the flowchart in Figure 4.4, at the start of a short-term assignment cycle, a pre-determined number of tokens is allotted to interested participants.The total number of tokens or the size of the token bucket for a participant is dependent on several factors such as the market cap, spectrum already owned, previous market behaviour etc. If a participant enters midway through a cycle, a proportionate number of tokens (based on time left) is allotted. The tokens can be allotted in several ways – only once during the short-term access cycle, periodically, at a constant rate r_M tokens per unit time etc. They are also used to monitor market behaviour by reducing the number of tokens or the rate of replenishment, if a participant behaves in an anti-competitive manner. These variations are presented as Models in the subsections below.

Regardless of the token model used, the following is the process flow of a token-based scenario

1. Each participant in the spectrum market is allocated an individual bucket of tokens

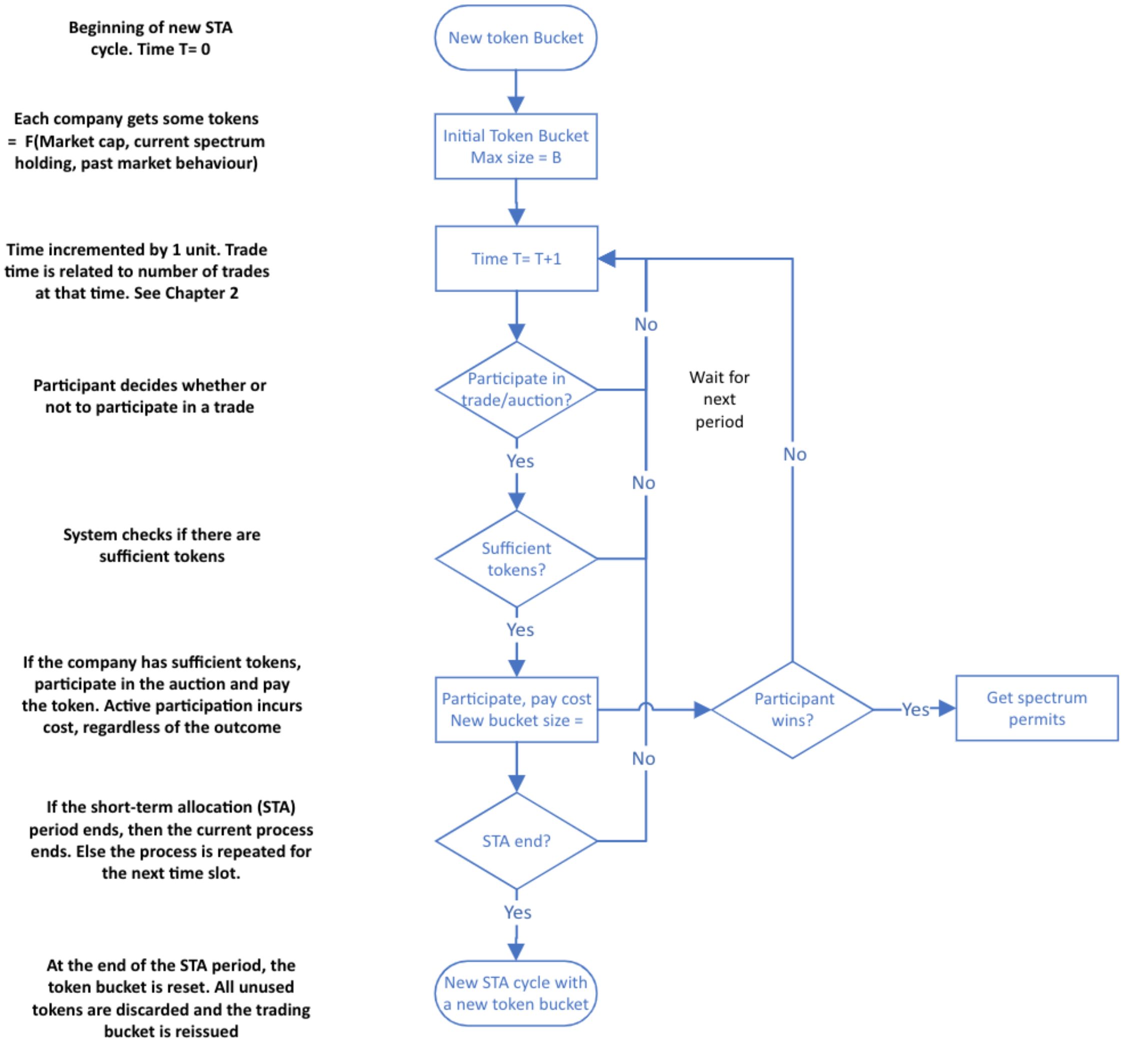

Fig. 4.4 Basic token model for BYOS framework

2. Participants decide whether to participate in the auction based on two factors – if they are interested in the lots on offer; and if they have sufficient number of tokens

3. Tokens are consumed when buyers participate in an auction. Active participate is counted regardless of whether a participant actually wins or the quantity of spectrum lots won.

4. At the end of the short-term access cycle, all the unused tokens are discarded and participants are issued a fresh bucket of tokens.

5. The market is self-tracking and self-governing, through the use of tokens. Tokens are used to both track buyer behaviour and spectrum ownership.

In the subsections the discussions focus on the variations based on different possibilities of how token assignments and penalties work.

4.3.1 Model 1

The first model is based on the idea that a bucket of tokens is allocated to each participant. the number of tokens allotted is determined as below:

$$Tokens_{initial} = f(Market\ cap, current\ spectrum\ holding, past\ market\ behaviour) \quad (4.2)$$

At the start of the next short-term access cycle, the bucket is discarded, and a new bucket of tokens is allocated to each participant.

Tokens are allotted only once during the start of a short-term access (STA) cycle. There are no mid-cycle replenishments. The operators can choose to spend their tokens at any of the short-term auctions during this cycle. Regulators calculate penalties based on unacceptable anti-competitive behaviour (discussed in the next section). Possible alternatives for penalising anti-competitive behaviour:

1. Participants are penalised only at the start of a new short-term cycle based on past behaviour during the entire short-term access cycle.

2. Participant behaviour is monitored continually, and tokens are taken away from the bucket whenever an offence has occurred.

3. Market behaviour is reviewed periodically during the short-term cycle and tokens are taken away in response

4. A combination of the alternatives 1 and 2.

At the end of an STA cycle, an overall participant market behaviour report is compiled, which is used to calculate the size of the initial token bucket for the next cycle. The Model I with Alternatives 1 & 2 for penalty is illustrated in Figure 4.5.

4.3.2 Model II

In this model, each participant has a bucket but is not allocated tokens. Instead, like the traffic model (discussed earlier), the tokens fall in the bucket at a rate r_T tokens/time period. In this case, the rate at which each participant collects tokens is determined by the operator type, size of their market and total spectrum already owned by the operator.

$$r_T(initial) = f(Market\ cap, current\ spectrum\ holding, past\ market\ behaviour) \tag{4.3}$$

Normally, the bucket has no maximum limit size for token bucket. This means participants can hoard as many tokens as they receive till the end of the STA period – after which the bucket is restocked again. However, when the short-term access cycle ends, the token bucket is discarded, and tokens are not carried forward to the next STA period. This means that it is counterproductive to hoard tokens for too long, as part of a long-term strategy.

Hoarding can further be restricted using the following two options:

1. Option I The token bucket has a maximum size, which is same for all participants. After the bucket limit size is reached, all new tokens falling in are discarded. This means, participants cannot hoard tokens beyond a certain limit.

2. Option II The token bucket has a discard rate. This rate may be made independent of the acquisition rate i.e. the rate at which tokens fall into the bucket. Discard rate can be varied to ensure that tokens are not hoarded above a certain level or for too long.

At the end of a short-term access cycle, an overall participant market behaviour report is compiled, which is used to calculate the initial token fall rate for the next cycle, as shown in Figure 4.6.

A variation of this model can be a cross between Model I and II. Here, tokens could be allotted periodically, e.g. at the start of every week, and participants can strategize how to spend the available tokens on the trade(s) in which they wish to participate.

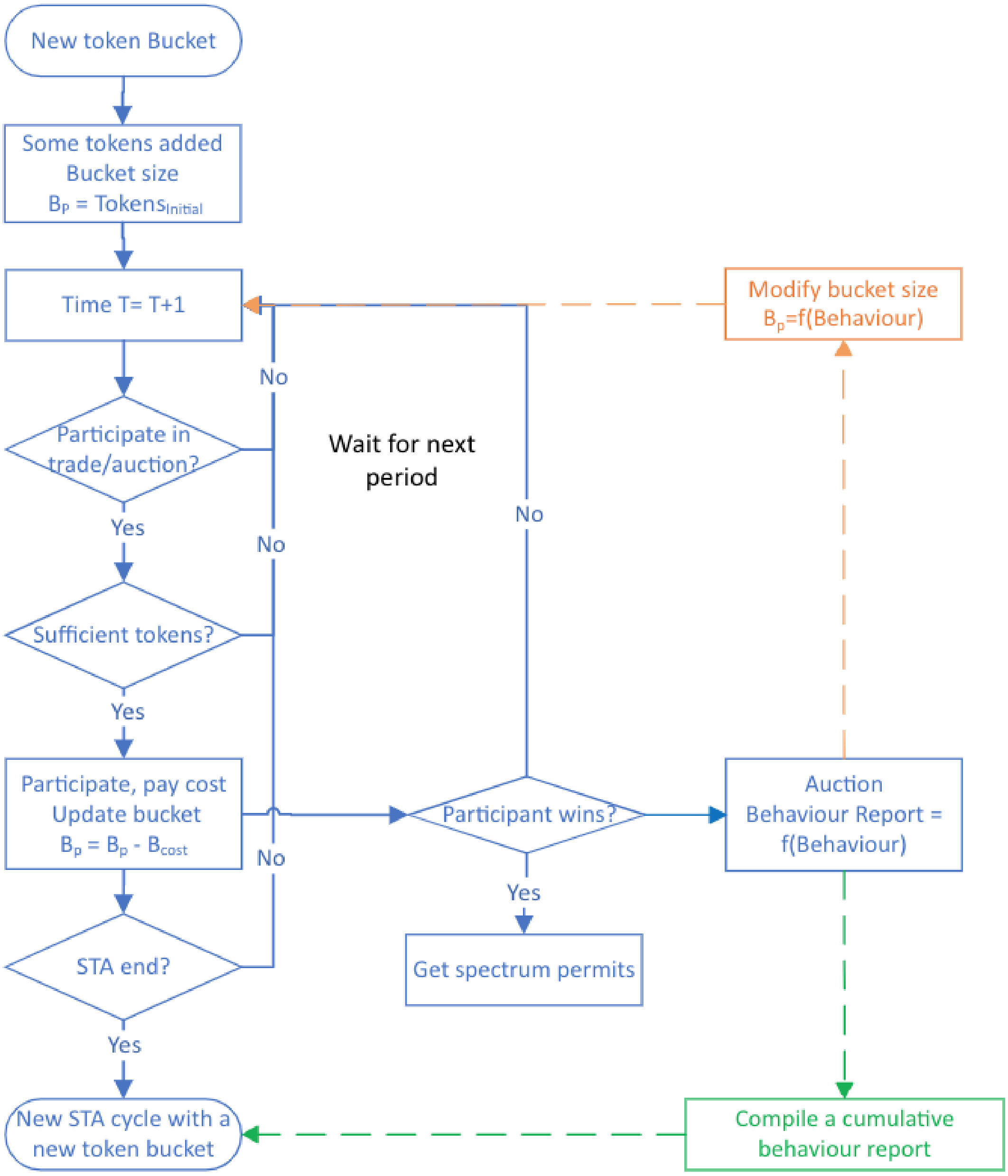

Fig. 4.5 Model I – Basic token process with alternative mechanisms to apply penalty

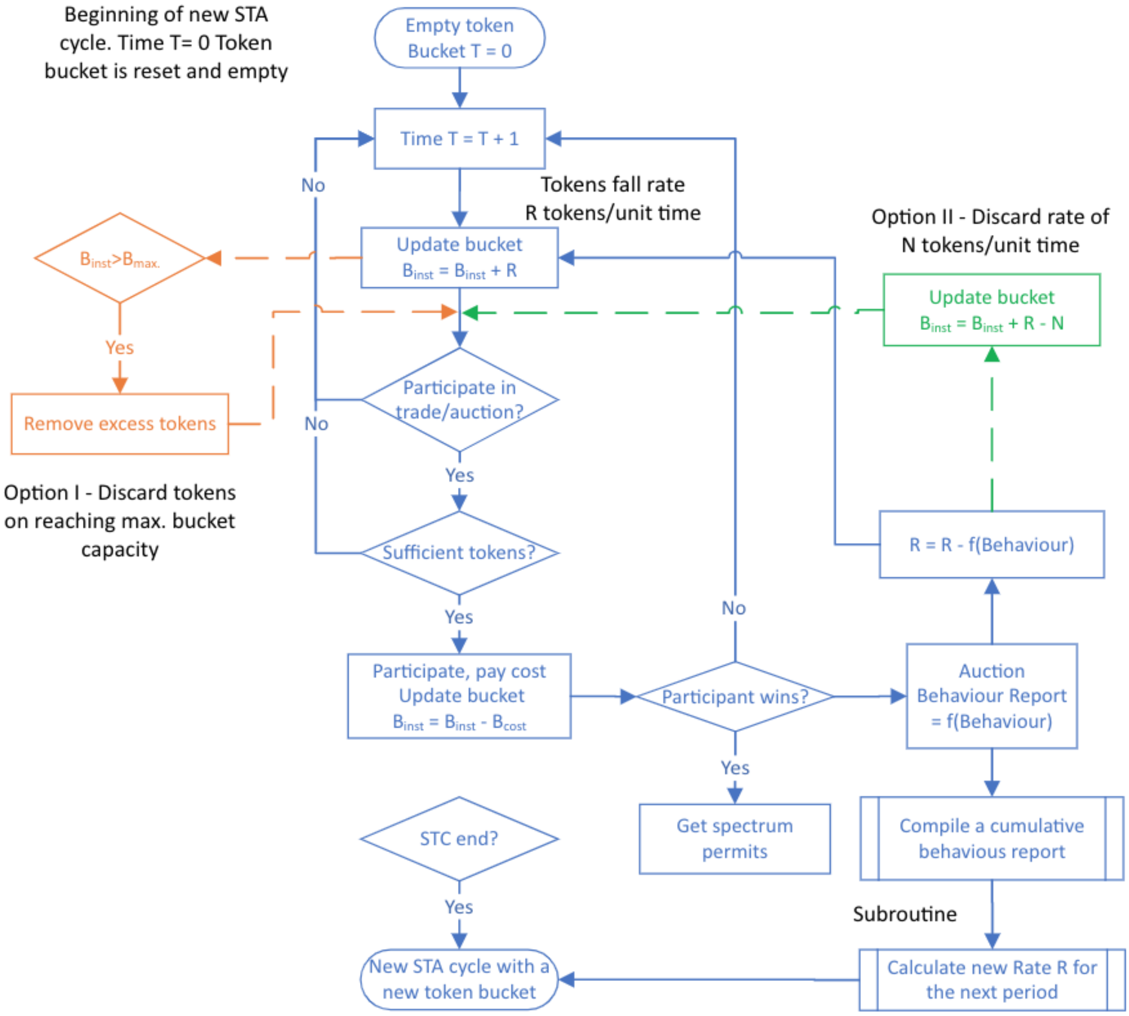

Fig. 4.6 Model II – Tokens fall in/out of the bucket similar to a leaky bucket

4.4 What is a token?

As seen in the previous section, in a network a token can represent different aspects of traffic flow. In this thesis, several options for what tokens can stand for, have been presented. A token itself can mean and represent different things, which affects the assignment process. Each type of representation has benefits and limitations. Following are the potential options

4.4.1 Option I: Token = Right to participate in an auction

$$1\ Token = Participation\ in\ 1\ auction \tag{4.4}$$

Tokens only represent the right to participate in an auction. This means that the bucket of tokens would represent the number of auctions a participant can actively bid on. Participation is counted regardless of whether a participant actually succeeds in an auction. Possible unfair or anti-competitive practices by other participants, are penalised by limiting number to tokens by measures discussed in the 3 models above:

1. For Model 1, the number of tokens can be reduced by either reducing the number of tokens to be acquired in future or by taking away tokens from the bucket.
2. For Model 2, the number of tokens can be reduced by either limiting the rate of tokens arrival or the leakage rate.

All short-term auctions are treated the same regardless of the period of acquisition or the quantity of spectrum lots acquired at each auction. This is the simplest mode of conducting the auctions. The reasoning behind Option I is that as most of the auctions are conducted over shorter periods of time, any penalties can be effectively applied for the future actions and there are no major long-term effects.

Conversely, the issue with this token model is that the big players can effectively only participate in selected auctions and distort the market for smaller players. As short-term market is mainly meant for smaller players to test their technologies, this could be challenging given their already precarious hold in the market.

4.4.2 Option II: Token = Right to participate in an auction, relative to acquisition period

In this model too, tokens only represent the right to participate in an auction. However, each auction participation is worth different number of tokens – more tokens for auctions that allow rights to be won for a longer period of time. Like Option I, participants pay the trading cost (i.e. the tokens) regardless of whether they actually succeed in winning a spectrum unit. Unfair or anti-competitive bidding behaviour management is also similar to the previous model.

As can be seen, in Option II, different auctions/trades have different weights attached to them, depending on the number of hours for which the spectrum rights are allotted. This weight is expressed in terms of tokens – participating in an auction that would allow the participant to secure spectrum rights for more hours incurs a higher cost, high payment leads to a better chance for more payoffs. Option II allows users to pre-plan their participation in a specific auction. If a participant fails to secure spectrum rights during a particular auction, especially one that would offer rights for a longer duration, they can choose to participate in auctions with lesser time duration.

A comparison of the two models is given in the table in Figure 4.7. As can be seen, in Option I all trades are considered the same and this means the maximum token bucket size for 1 day is 45 tokens – which gives a participant the right to actively participate in all auctions. In contrast, in Option II, each trade has a different weight attached – depending on the size of period (in hours) the participant can acquire rights for.

In both Options, the quantity of spectrum won at each trading period is not related to the token bucket. The advantage here is obviously a simpler model and with the burden of market behaviour placed on the number of tokens allotted to the participant. Market behaviour also includes the percentage of spectrum rights already owned by a single participant.

An obvious limitation is that, treating all spectrum rights under one single variable of spectrum ownership makes the ownership less transparent. Even in the current model of ownership, it is easy to determine who owns which part of the spectrum and how that generally impacts the market rights of the participants. Because of the different physical characteristics of the spectrum band, all spectrum rights cannot be treated in the same manner.

To solve these issues, a unified quantisation model of the spectrum has to be used, which has been discussed using emission rights in Chapter 3. The section below presents a discussion on pollution permits and different elements of this idea.

Time	Period of ownership (in hours)					Max allotted tokens	
						Option I (= Total auctions in this hour)	Option II (= Hours for which rights can be acquired)
0	1	2	4	8	16	4	31
1	1					1	1
2	1	2				2	3
3	1					1	1
4	1	2	4			3	7
5	1					1	1
6	1	2				2	3
7	1					1	1
8	1	2	4	8		4	15
9	1					1	1
10	1	2				2	3
11	1					1	1
12	1	2	4			3	7
13	1					1	1
14	1	2				2	3
15	1					1	1
16	1	2	4	8		4	15
17	1					1	1
18	1	2				2	3
19	1					1	1
20	1	2	4			3	7
21	1					1	1
22	1	2				2	3
23	1					1	1
Total tokens						45	112

Fig. 4.7 Comparison between two options for what tokens stand for

4.5 Extending BYOS framework details

4.5.1 What does 'winning an auction' grant?

Winning an auction or a trading agreement between two parties grants an access to one or more pollution permits. This information provides the information on the amount of spectrum bandwidth an operator has access rights to and the quantity/type of emissions. In this work, two alternatives have been proposed for what a permit represents.

- Alternative I: This is a simple quantised measure, where 1 permit represents spreading 1 unit of pollution (power) across 1 unit bandwidth.

$$1\ Permit = 1\ unit\ noise \times 1\ unit\ bandwidth \tag{4.5}$$

  The literature focusing on spectrum usage-type permits makes use of a similar measure to represent the trading unit [161, 162]. The advantages of this type of unit is that it is an absolute quantity of power spread and can theoretically extend in multiples, according to either capacity or population measure. The limitations of the measure are that noise or effective power (necessary for effective communication) is technically complex to estimate and varies on several factors such as regional topography, weather and atmospheric conditions. These reasons have already been cited by researchers as a reason why noise or power measures are very complex to be used as absolute trading units, at least based on current technology.

- Alternative II: Based on research in this area, a novel method of representing a permit is proposed here. Recall from Chapter 3 that spectrum access can be either in the form of spectrum holes (overlay and interweave access methods) or below a certain threshold (underlay access method). Using this information, sellers can offer three type of permits in the market:

  - Exclusive access permits (PT-1) – As the name suggests, this type of permit grants access to a buyer gaining exclusive access to a particular band. Apart from legal/safety radiation limits as well as interference constraints from nearby regions and frequency bands, the buyer does not have any other restrictions in the level of noise or power they are allowed to spread over the designated bandwidth. Needless to say, this type of the permit would be the most coveted, the most in demand and hence the most expensive to obtain.

- Percentage access or shared permits (PT-2) – This type of permit refers to shared access with one or more operators. In this case, the primary user offers a percentage of bandwidth usage to interested buyers. Sellers can offer access in the following ways:
  * Spectrum holes in time: For a given bandwidth, buyers are allowed to transmit a specified amount of power per unit time (when the primary user is not operating). The timings of transmission can either be coordinated with the existing user or an overall percentage of allowed transmission per unit time is allowed. Either way, the rights can be offered in terms of percentage of usage allowed per unit time.
  * Capacity per unit time: Buyers are allowed to partially piggyback on an existing system (i.e. primary operator's RAN). The purpose is to achieve target capacity without affecting the resource constraints or QoS expectations imposed by the primary operator. The limits can be converted in terms of a percentage of $power \times bandwidth$ of primary user and offered in the market.
  * Narrowband access: The narrowband access techniques defined in 3GPP Release 13 – NB-IoT and LTE-M – are designed to coexist with the existing LTE network. They make use of a pre-specified fraction of the network, which is essentially a slot or *hole* in frequency band-time and a given power level. For instance, NB-IoT works at the same power level as LTE network (23 dBm) and uses 1 in 25 slots (for a 5 MHz LTE network). In the same way CAT-M1 has 2 options either 20 dBm or 23 dBm and uses 6 out of the 25 slots for a 5 MHz LTE [167]. In both cases, the usage can be expressed in terms of $(power \times bandwidth)$ percentage of the primary user for selling access.
- Below threshold access permits (PT-3) – This type of permit grants the buyers to spread power (i.e. noise) below a minimum level of threshold that won't affect an existing operator, and both can exist in tandem. This type of access technique is known as underlay and is used by ultrawideband technologies. The power spectral density emission limit set by FCC is -41.3 dBm/MHz. Below -41 dBm can be considered as one unit of power spread over a large bandwidth, regardless of the actual levels. This type of permit can work with both PT-1 and PT-2 type permits, unless there are specific concerns specified by primary users disallowing access to the bands.

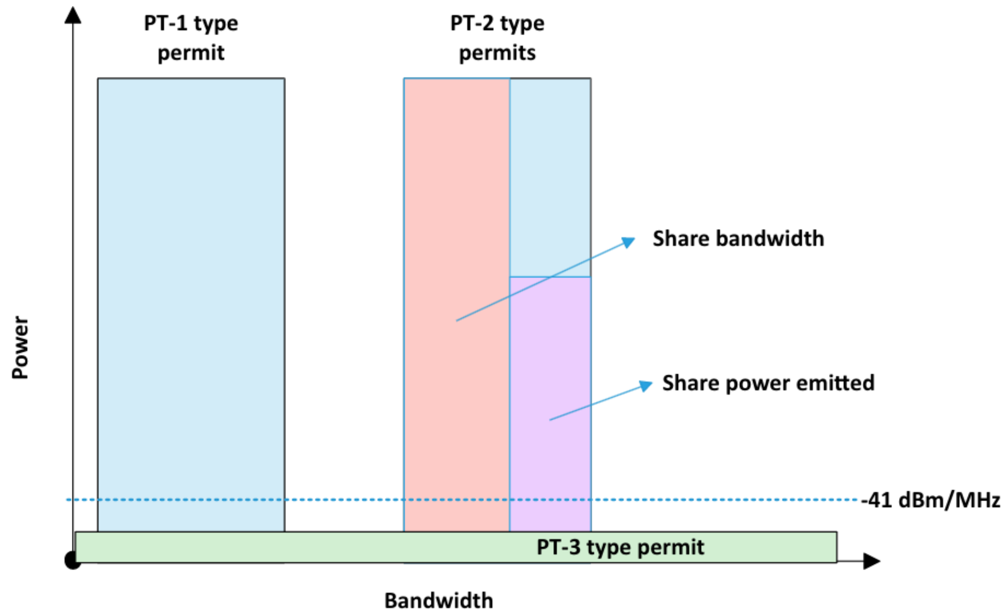

Fig. 4.8 Illustration of different type of spectrum permits

4.5.2 Characteristics of spectrum lots

It is assumed that at any given point in time there are some spectrum lots comprising of a set of pollution permits for a given region available for purchase. Not all of these will be utilised as buyers in the market may not be interested in purchasing them for various reasons. The term Technical Application Suitability Factor (TASF) was introduced in Chapter 3 to express the attractiveness of a spectrum lot to its owners.

As mentioned, attractiveness of a spectrum lot is defined by its characteristics. The characteristics are of the following three types:

- Physical characteristics – These are the best known and most researched characteristics. Spectrum bands have basic physical properties that affect their propagation and coverage characteristics. For instance, the relationship between wavelength and corresponding resilience against fading and blocking decides the wavelengths better suited for areas requiring extensive coverage. Lower frequencies are often seen as a better option for commercial services that have to build the network around existing landscape obstructions like buildings and terrain. Lower frequencies (below 1 GHz) also require less infrastructure to provide similar coverage, and consequently they are more attractive to commercial operators. These frequencies however are limited in their ability to provide capacity because of low reuse capabilities. A balance between coverage and capacity needs has led to operators look for more heterogenous solutions.

- Location characteristics – Consider a wireless network deployed in a location with three regions – urban, suburban and rural. Urban locations have high population density and high data demands during definite peak periods that are periodic. The demand falls off drastically during off-peak period. Suburban locations have comparatively much lower data density, there are definite peak periods where the population rises, but there are usually sufficient alternative mechanisms of communication such as non-cellular Wi-Fi and wired connections. Rural deployment is characterised by low population density, lower demand and no definite prominent period. The population is usually distributed over a larger area and there are no ubiquitous alternative mechanisms for communication, as in suburban areas. Because of low return of investments, the competition in these areas is low. This makes rural areas very good test beds for newer technologies. For operators (both buyers and sellers) spectrum in each region has different utility values which is defined as a function of consumer demand factor, infrastructure deployment and maintenance costs, and competition. In the traditional long-term spectrum acquisition model, location factor need not be considered as capacity and coverage is calculated for maximum usage in advance. This in fact is one of the primary reasons behind inefficient spectrum usage and the artificial spectrum scarcity.

- Band proximity – This factor was a consideration for operators acquiring spectrum in the traditional long-term spectrum acquisition model. While newer generations like IEEE 802.11 and LTE support carrier aggregation from similar and dissimilar bands, it is well known that aggregation comes at the cost of performance and that larger channel width provides benefits such as lower power spectral density, improved geolocation and higher data throughput rates. Thus, it is logical that contiguousness and proximity to the currently owned spectrum band would be more attractive to operators. This factor is however specific to each operator and the attractiveness score for the same spectrum lot would be different for different operators, depending on the technology used. For instance, if an operator is using ultrawide band technology and has emissions under the FCC prescribed –41.3 dBm/MHz, other operators may be more interested in shared access than with another operator using a narrowband technology within the same frequency bands.

- Exclusivity – Because of the advent of cognitive radio and dynamic spectrum access principles, the idea of spectrum sharing between two parties was actively introduced. This is different from the secondary spectrum market ideas prevalent in 1990s, where a spectrum license bought by a primary buyer was then resold to a secondary buyer for a fee. Spectrum sharing involves two or more operators actively sharing the same frequency band, often at the same time. This would involve additional processing overheads to coordinate access between different radios, which operators might not be interested in, with respect to their demand requirements. Hence, this is another factor that might impact interest of operators in the available lots.

- Time factors – The BYOS framework brings two new factors affecting the desirability of a frequency band as discussed below:

  – Period of acquisition – Any operator would be interested in winning continuous spectrum holding for a longer period of time. Hence, the operator would be willing to pay more for long term period of acquisition for the same frequency band.

  – Peak acquisition – For shorter acquisition periods, the cost of acquiring spectrum would logically be higher if the demand is higher and it is the peak period in a busy location. The peak acquisition period is not applicable for all areas. This factor is dependent on whether an operator needs extra capacity in a given region at a given time. There may be an upsurge of requirement if, for instance, there is a show or a match at a particular location.

TASF determines the interest a buyer has in a particular spectrum lot and the price

4.5.3 Role of infrastructure in mobile networks

As spectrum is a medium of information transfer, significant cost is expended to build the infrastructure around the assigned spectrum. This is naturally a part of the balance sheet of the mobile operators when they calculate return of investment. This is one of the primary reasons why long-term spectrum auctions are considered to be the core mode of assignment for the foreseeable future and cannot be delineated from spectrum itself.

In the proposed framework, infrastructure and related costs are not specifically mentioned as part of the acquisition process. The reason is that the trend towards intelligent base stations for providing the services [182]. The thesis works on the assumption that cognitive networks and base stations would be the way to the future – band and technology agnostic. Software defined networking has already made strides in this area in terms of:

1. Self-organising network, as defined in [182] refers to mobile network automation and minimization of human intervention in the cellular/wireless network management
2. Docitive networks, as defined in [183] refers to the networks where nodes essentially teach other nodes with the prime aim to reduce cognitive complexity
3. Enhanced node B operations that can offer last mile sharing of radio networks

In addition to this, the narrowband example given in the last section focuses on using the existing LTE network to provide narrowband services, so infrastructure is effectively shared between the two services.

The thesis postulates that, in the future two or more parties would be able to provide the required infrastructure, operating as wireless infrastructure companies. This is basically the principle behind the LTA scheme. The infrastructure firms can then "sell" the infrastructure – either on their own for companies to choose from or as a package with the spectrum attached e.g. is the way virtual network operators work.

4.6 Summary of Chapter 4

Expanding the technical aspects of the BYOS framework in Chapter 3, this chapter presents the ways in which competition can be managed in the framework. This part is important for several reasons. First, sub-optimal results to induce competition by the government suggests that the markets develop naturally without intervention, which (from the cases of Germany, UK and India) have only delayed the processes and caused losses. Second, government-free situations in the sector (such as pre-1912 era and the 1980s lotteries era in US) have both resulted in chaos. The logical option is hence to try a hands-off approach, where government maintains a regulatory oversight, with the power to penalize anti-competitive behaviour, but participants are free to interact with each other. The infrastructure related discussion in Chapter 2 shows that this type of intervention may not have worked in the past because of the long-term monetary investment in a particular set of frequencies. However, Section 4.5.3 shows that the trend is now towards intelligent networks that allow coexistence between multiple technologies, making the case for short term ownership.

Thus a novel, network-traffic-management based competition management scheme is proposed – the tokens. The chapter presents various deployment models that can be chosen.

Token-based competition model is intended only for short-term access periods in the BYOS process, though the initial bucket size (for each STA period) is dependent on cumulative review of behaviour. The chapter also discusses the definition of token, discussing whether it should be independent of the acquisition period. The thesis does not recommend a final solution, which would require extensive modelling. The experiments and simulations conducted for this chapter where simplistic and did not provide sufficient justification to choose any one or a set of solutions, hence are not included as a part of the discussion. Instead competition in the sector is modelled using a series of "games" to show different scenarios of ownership. This is covered in Chapter 5.

Chapter 5

Ownership games

This chapter presents a discussion of different possible competition scenarios and how they are handled within the proposed framework. The main purpose of this chapter is to show how different types of operators fit into the framework and how to manage flexible framework assignment. The chapter uses elements of auction and game theory and hence starts with a discussion on the applicable concepts of the theory. Different players are then introduced into the framework and illustrative games are used to cover different competition scenarios.

5.1 Theoretical background

In this chapter formal representation of the working system are presented using indicative examples. This is done by making use of a special class of games of incomplete information known as mechanism design. Before explaining mechanism design and how the concept is applied in this work, some basic terminology of applicable game theory concepts are discussed.

As any trade will have at least two players, possibly more, the space can be represented using a game theoretic approach. The game space in this case is defined as mobile network operators (including virtual operators) participating in a spectrum access trading system in a non-cooperative manner to maximise their payoff. The game outcome is a decision of whether an operator decides to participate in the trade, given its individual payoff scenarios. Game theory is almost synonymous with auctions, especially in the spectrum domain, and has often also been used for assigning resources in dynamic spectrum access scenarios. The approach followed in this thesis is different because game theory is applied to the decision of whether to participate or not, and the consequent payoff, rather than to the process of resource assignment itself.

Cooperative games are where multiple decision makers act as a group, while in non-cooperative games the decision-maker acts independently from all other decision-makers [184]. During spectrum auctions, each organisation will act independently of other companies, even though these decisions may be influenced by other companies. Hence, non-cooperative game theoretic approach has been used to model various cases.

Mechanism design has been defined as *"reverse engineering of games, where rules of a game are designed in order to achieve a specific desired outcome"* [185, pg. 205]. The focus here is to design a framework or a system, where individual agents, interacting within the framework will act strategically and may also hold private information that will help them forming decisions. Mechanism design, instead of finding equilibrium solutions to a game, focuses on developing the rules and settings of the game to create desired incentives. The objective is policy makers induce a game between agents, with incomplete information, in such a way that the desired solution for system-wide implementation is achieved in an equilibrium of the game [184, 185]. In this section a review of of applicable concepts in auction theory and game theory ifs presented.

5.1.1 Auction mechanisms

The term auction is defined as a market clearing mechanism to equate demand and supply. Other well known trading mechanisms are bargaining and fixed-price[186]. Here a brief overview of different trading practises is presented as a background, including the main types of auction, taken from multiple sources [186–188]. Bargaining is usually a part of trades such as purchase of a house or a second-hand car, while fixed prices are the mode of trade in standard retail sector. When seller knows the exact prices of goods based on existing demand (by experience and observation), fixed price is usually used. In contrast, bargaining happens between one buyer and one seller at a time to obtain the best possible price. However, when demand is greater than supply (such as in case of spectrum resources) auctions are used to assign the resources. Auctions can be open-bid, where all bids are openly visible to all participants or sealed-bid, where bids are closed to all, except the seller. Open auctions can further be of two types, ascending auctions or descending auctions. Ascending or English auctions are where bidding starts from a preset reserve price and goes up until it reaches the price where demand equal supply. In contrast, descending or Dutch auctions start at the highest possible prices. The bidder watch the prices decline until they reach the price which at least one of the bidder accepts, thus leading to demand-supply equilibrium. Then there are the first-price auctions, where the winner pays the highest bid, versus second-price or Vickrey auctions, where winner pays the second highest bid. Finally, there are the single and multi round auctions – self explanatory, based on names. Variations of ascending auctions are simultaneous multi-round auctions (SMRA) and combinatorial clock auctions (CCA), discussed in Chapter 1, that use several complex rules to allow package bids involving multiple size spectrum lots. With the possible exception of Dutch auction, all auctions have been used for assignment of spectrum and hence have been evaluated for their effectiveness.

Comparative research on the merits of one auction over the other has usually focused on discouraging anti-competitive behaviour such as collusion [55, 137, 189] or revenue equivalence [186]. The following are key known anti-competitive behaviours during auctions:

- Winner's curse – This refers to the situation where aggressive bidding causes one of the participants to win but at a price that is too high when compared to market consensus [187].
- Bid shading – This is when buyers pay a lower price than the market valuation to buy resources at a much lower cost. Bid shading is not necessarily an anti-competitive practise. One of the purposes of bid-shading is, in fact, to avoid winner's curse in a common-value auction (i.e. where the perceived value of item for sale is same amongst

all bidders) with incomplete information [176]. However, bid-shading could also lead to assignment inefficiency especially when bidders with identical marginal values reduce their bids by different amounts. This means that the auction is no longer truthful making it impossible to award items to the bidder who values it the most [186].

- Bid rigging – Bid rigging involves groups of firms colluding engage in behaviour such as to price fixes or only bidding for specific slots etc, so that they are able to win the lot or items etc at lower prices [186].
- Predatory pricing – Predatory pricing refers to issues where large bidders engage in fixing prices such that one or more of the other bidders are forced to leave the auction [186]

This thesis does not focus on any specific form of trading, rather it is about making sure that unfair practices are kept at a minimum within the framework. While designing the specific auction type is important, for shorter term periods, it would be more efficient to allow faster trading, with checks to discourage collusive practices. For trades over medium term, the regulators are free to choose the mode of auction, based on their requirements, as is the current practise. Hence, this chapter focuses on designing the mechanisms of a trade (not actions within it), so that participants have no incentive to engage in predatory pricing.

5.1.2 Components of a game

A strategic game is defined by four components:

- **Decision-makers**, also known as the **players** in a game. In this thesis, the players are the mobile operators. Players can be grouped into categories, known as agents, where each agent-type determines specific characteristics. For instance, operators can be categorised into incumbents and new-entrants. The new-entrants can then be categorised based on the services e.g. MNOs, MVNOSs etc.
- **Options** players can choose, also known as the **strategies**. If there are multiple stages of decision making e.g. chess, the games are called extensive form games. A multi-stage auction is an example of extensive form game.

  In this thesis, the decision making is limited to whether a participant chooses to participate or not and the participation form (fair-unfair play) decides the payoffs. As seen from the previous chapter, tokens are allocated to participants either at the beginning of the shortest medium-term access period or they trickle down at a predetermined rate. The organisations are free to participate in any trade, so long as their ownership limit does not exceed the specified limits that forms a monopoly. Spectrum lots can be free at any given point in time, which means that it is in the best interests of the operators to ensure that they are able to participate in the short-term trade, if required. This also means they can participate in a trade to affect prices, rather than winning spectrum, attracting a penalty. A case in point is the aggressive bidding during Australia's 1800 MHz auctions in 2000, discussed in Chapter 1. Also as mentioned in Chapter 1, US spectrum auctions have also frequently attracted accusations of anti-competitive bidding practises. So there would be a case for analysis as an extensive-form game, where organisations strategise to gain as much spectrum they can, while also making sure to keep tabs on their opponents.

However, extensive-form game is not considered because of several reasons. First, the token bucket size (i.e. penalty) can be recalculated for repeat offenders by the regulators acting as a deterrent. Second, the focus is to achieve maximum spectrum usage, so practices like exceeding ownership limits cannot automatically be considered as anti-competitive. Finally, the short-term access period means that market corrections are possible at the next period, where specific concessions can be granted as award (as opposed to penalty) to other operators, thus boosting the market. Hence, the strategy of the regulator is to observe the market at each stage and decide on implications for the next stage.

- **Objectives** in choosing an option, or the **payoffs** received. Each player evaluates all possible endings of a game i.e. the outcomes and assigns real numbers i.e. payoffs to them. The payoff of players depends not only on their own strategy but also on the strategy choices of all other players. This is the payoff function, which relates all possible strategy sets from all players to real numbers representing the outcomes. Usually the overall objective is to achieve the largest positive number possible as the outcome, depending on the potential strategy of the other players. This is also known as rationality hypothesis. It is clear that a single player cannot determine the outcome of a game or its own payoff value. Hence the solution cannot be found using simple optimisation, instead this is a social optimisation problem that often has conflicting optimisations.

In this thesis, each player can make a decision table based on what would happen if they win/lose at an auction i.e. a competitive trade and the payoff if they behave in a fair/unfair manner. This is illustrated below

Result	**Behaviour**
Win Auction	Fair/Unfair
Lose Auction	Fair/Unfair

The particular payoffs are in terms of the number of tokens lost during the trade. In a fair trade, the number of tokens lost is pre-determined e.g. 1 token/trade or 1 token/hour of ownership etc. Unfair means may achieve the desired result, but the payoffs are negative – determined by the regulator using their own mechanisms. This means that it not only matters whether the player wins or loses a competitive trade, the determination whether the player was fair or not also impacts the result. This is the novel point of distinction in this thesis. In reality, unfair behaviour itself can be of two types – price-based (e. bid shading, bid rigging, predatory bidding, collusion etc.) and ownership-based (spectrum exceeds the limit prescribed legally as monopolistic). First, both are evaluated as generic unfair behaviour with common payoffs.

- **Information** about the structure of interaction, or **knowledge**. In cases where all players know the set of all players, strategies of each player and all their payoff functions, the game is said to have complete information. Otherwise, the game has incomplete information. A simple game such as a coin-toss or even prisoner's dilemma are examples of complete information problems.

  In the present case, trading at any given time comprises of players, whose identities may or may not be known. While this information is reasonably easier to determine, what is not known is the size of the token bucket for all players, the specific strategy chosen for the particular trade (in terms of budget allocation) etc. This means that this problem is essentially an incomplete information problem.

A non-cooperative game can be represented as a system shown in Equation 5.1

$$G = (N, S_i, H_i) \tag{5.1}$$

As can be seen, there are three elements to the above representation.

- N – A finite set whose elements are called players. $N = \{1, 2, \ldots, n\}$ In this case, this is the participants in the framework who agree to enter into a trade.

- For each player $i \in N$, $S_i = \{s_{i1}, s_{i2}, \ldots, s_{im}\}$ represents an element from the set of strategies of all players for all possible game situations. The ordered sets $\{x_i\}_{i \in N}$ of the strategies of players are the elements of the Cartesian product:

$$S = \prod_{i \in N} S_i$$

  In the proposed framework, there can be multiple ways to represent strategy – how much to bid, maximum value, etc.

- For each player $i \in N$, the bounded functions $H_i : S \to \mathbb{R}$ are the payoff functions of the players and their values on the situations are the payoffs in these situations.

5.2 Payoffs in a 2-player single auction game

Assume that at time t, a spectrum slot is available and player P1 and player P2 are interested in acquiring the slot. Both represent MNOs of equal size. Also assume that the two players have similar motivations for acquiring the spectrum lot (i.e. same valuations) . For simplicity, it is assumed that this is a zero-sum game, at this point. This means, only one player can win the indivisible slot (the other payer loses). The problem then simplifies into an entry game[1] albeit with different payoffs. As mentioned in Section 5.1.1, valuations attached to specific auctions are not considered at this point in the discussion. All auctions are considered equal at this point. Before starting the bid, both players are expected to submit their initial valuations (initial bids) for the lot. This is done to determine the baseline for the price of the spectrum lot. Spectrum auctions have been conducted throughout the world for over 3 decades. The research on reserve prices has also been exhaustive, and has been used by regulators to set reserve prices for a given spectrum lot. In this framework, the background on reserve prices is only used to inform if the valuations are unfair leading to assignment inefficiency. The focus is on setting prices based on individual participant valuation of the available spectrum lot.

Payoff calculations can be done using the following assumptions:

- Winning the auction is equivalent to +2 payoff
- Tokens cost for appearing in 1 auction is equivalent to -1 payoff

[1]Entry game is where an incumbent monopolist faces the possibility of a new entrant in the market, in the form of a challenger. The challenger must decide whether it should enter the market or not. Based on this decision, the incumbent decides whether to concede or fight (i.e. price war).

- Penalty cost if price exceeds equivalent to -2 payoff

The payoffs are simple if the other player opts out. The spectrum auction reduces to a simple trade between 2 parties. There is no issue with fairness (unless the price set by seller is too high). The payoff assumptions are simplistic and are based on the simple idea that losing tokens is considered a loss because only a limited number are allotted during a short-term cycle and the loss affects participation in future auctions. Winning the auction, however, is the goal of the participant (unless they are non-genuine participants, in which case the payoff will probably be different). Hence, it has a higher payoff value (and positive). The penalty cost here is shown as a tentative number. This specific number is decided by the actions of the regulator such as additional loss of tokens and is stiff enough to act as a deterrent. The payoffs are tabulated in Table 5.1.

	P1 opts out	**P2 opts out**
P1 payoff	0	$+2-1=+1$
P2 payoff	$+2-1=+1$	0

Table 5.1 Step I – Decision to participate in an auction

The game begins, when the players decide to start a price war. If both the players play fairly and one of them wins, no extra tokens are charged. This is shown in Table 5.2.

	P1 has the winning bid	**P2 has the winning bid**
P1 payoff	$+2-1=+1$	$0-1=-1$
P2 payoff	$0-1=-1$	$+2-1=+1$

Table 5.2 Step II – Participation in a fair auction

Consider one player aggressively bidding for the spectrum hence forcing all participants to increase their bids, potentially leading to winner's curse type of scenario. In this case, equal player sizes and equal valuations, this is easy to determine. The motivation could be either driving the opponents out of the market and win the spectrum or ensuring that the opponents win but at a higher price than the valuation. Once this price is triggered, both bidders are considered to be in violation and incur extra token penalty. This is shown in Table 5.3.

	P1 has the winning bid	**P2 has the winning bid**
P1 payoff	$+2-3=-1$	$0-3=-3$
P2 payoff	$0-3=-3$	$+2-3=-1$

Table 5.3 Step III – Participation in an auction when players are aggressive

However, once one of the player's bids exceeds the threshold the other player also has the option to concede. In this case, the player conceding does not incur the penalty cost as shown in Table 5.4. An obvious limitation of this simplistic scenario is that an unfair player might lead competitors to the limit price at which the token penalties apply. However, as all the auctions are for short term acquisitions without rolling over of the ownership periods, more participant behaviour samples are available for tracking. Also, short-term ownership ensures that hoarding period is reduced, giving less incentive to participants for undertaking shady bidding practises.

	P1 concedes, P2 wins	**P2 concedes, P1 wins**
P1 payoff	$0-1=-1$	$2-3=-1$
P2 payoff	$2-3=-1$	$0-1=-1$

Table 5.4 Step IV – Participation in an auction when only one player is aggressive

Figure 5.1 shows a tree diagram of the game discussed above. The blue lines show the decisions made by player P1, while the orange lines show the decisions made by player P2. The payoff after the decision are shown in brackets in (player P1, player P2) format

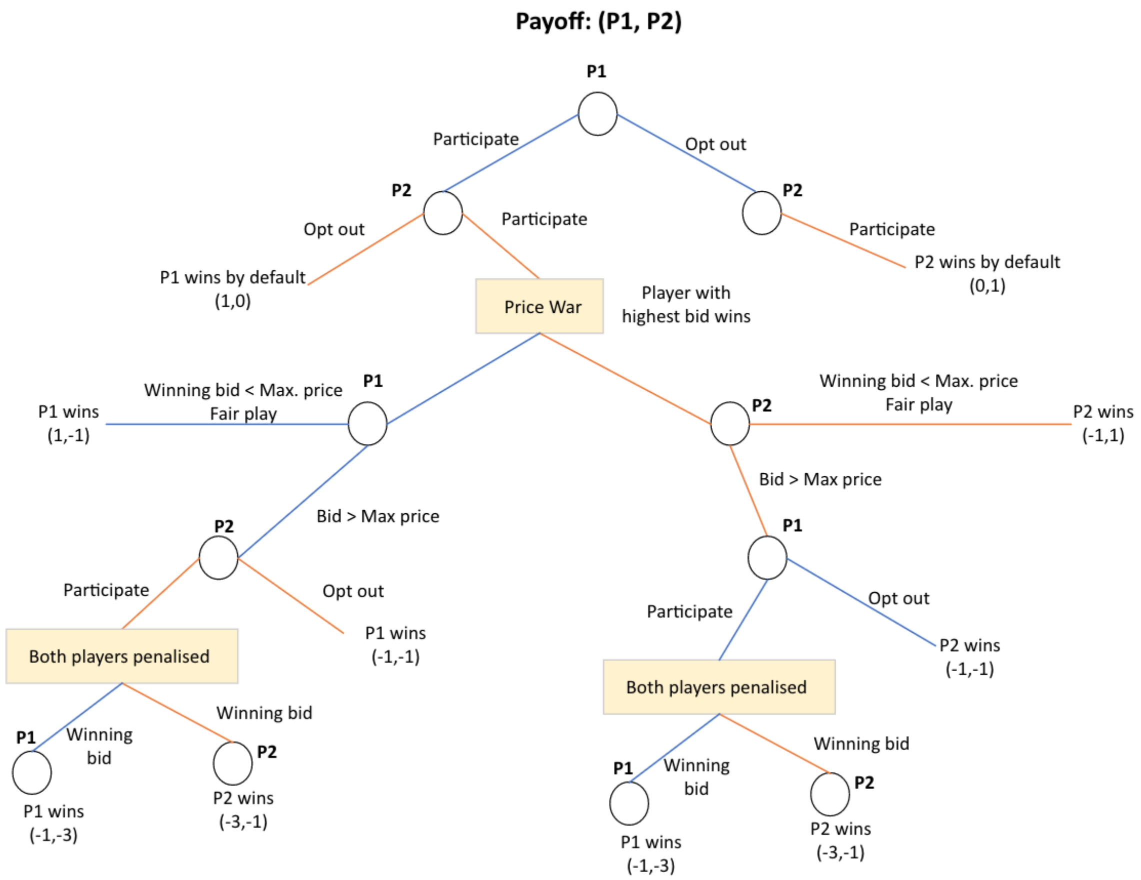

Fig. 5.1 Tree diagram of a simple auction game with 2 players using tokens
Blue lines: Actions of P1, Orange lines: Actions of P2

The assumptions express a simplistic view of what it means to win and lose at this stage. From the tokens discussion in Chapter 5, let the trade use Option I i.e. 1 token is charged for each trade, regardless of the length of period of ownership. As there are no other players in the market, this is a reasonable option to choose. The model used is Model I, i.e. players get a fixed bucket of tokens in the short-term access period (the period of modelled in this chapter). Losing tokens represents a loss. In simplest case, loss of 1 token = -1 payoff. Winning an auction is a desirable outcome, so the payoff should be +2 at a minimum, for a net positive payoff. The payoff values are representations of winning and losing. In this exercise, tokens and winning a spectrum lot have the same value. This is a reasonable assumption to make based on available information – if a participant does not have tokens, they cannot participate in the auction. The actual relationship is complex and would depend on the size of the token bucket, current customer demand profile defining interest in acquiring spectrum etc.

5.3 Valuation and payoffs

5.3.1 Case 1: Basic case as a Bi-matrix

In Table 5.1, it assumed that the payoff for winning an auction is $+2$ for both the players. This was chosen for illustration purposes, as discussed above. The payoffs for winning auction actually differ based on how much winning an auction is desired and is used to decide whether the operator should move towards active participation. This is shown below.

Table 5.1 can also be represented using a bi-matrix as shown in Table 5.5. The values in the cell where both players participate are given as the probability of winning for each player. The values have equal probabilities as these are two MNOs of equal sizes – both incumbents, with similar customer base, and with similar value of spectrum acquired during long and medium-term access periods. Continuing to compete will mean that the players have to pay 1 token each, and the probability of winning the next stage (i.e. 2 payoff) is 0.5. Thus, pay off will be $(2 \times 0.5) - 1 = 0$ for each player

		player P1			
		Opt out		Participate	
player P2	Opt out	0	0	0	1
	Participate	1	0	0	0

Table 5.5 Payoff as a bi-matrix

As can be seen from above, if the valuation for both the players is $+2$, then both players are no better off participating and competing in the auction.

This is not an incorrect assumption, however. It fits the scenario where the operators are discovering the market and would not mind gaining spectrum but don't wish to spend more resources. This is also equivalent to base stations (or transmitters in general) idly looking for better networks (opportunistic access). If there is no competition, they can make use of the resources to provide/obtain better services.

5.3.2 Case 2: Winning is valued higher than token loss

If a player seeks to participate in an auction because they wish to acquire the spectrum for specific purposes, then the valuation and hence payoff would increase. As an example, consider a scenario where there is a special event occurring in a particular region e.g. a city holding a major event. In this scenario, a large number of people would be expected, all with their own radio devices. Legacy spectrum owners may on this occasion choose to allow operators to access radio channels for communications. In this scenario, winning a newly opened spectrum slot would be highly beneficial in terms of revenue, so the payoffs would be higher. Assuming a payoff of $+5$ for each player, and with the same standard loss of 1 token for participating in the auction, the payoffs given in Table 5.5 are recalculated. For this scenario, the same assumptions are valid as before – zero-sum game between equally sized mobile network operators. The probability of winning would be the same i.e. 0.5.

So, payoff, in case one of the players decides to opt out would be: $+5-1=+4$ And, payoff in case both players decide to participate would be: $(+5\times 0.5)-1=1.5$

The bi-matrix for the payoffs is shown in the table 5.6.

		player P1			
		Opt out		Participate	
player P2	Opt out	0	0	0	4
	Participate	4	0	1.5	1.5

Table 5.6 Payoffs in a 2-player game for acquiring spectrum for special purpose

It can be seen that player P2 will never choose to play opt out, because its payoff would always be 0. Similarly, player P1 will never choose to play opt out because it payoff would always be 0. So, both the players will choose the participate strategy in this case.

The type of operator not only affects the probability of win, but also affects the valuation of the spectrum lot. For instance, if one of the players P2 is a new entrant trying to establish an operation. Because of the player size, it hasn't been able to purchase spectrum lot in the long- or medium-term market. It holds some type of infrastructure sharing agreement with an MNO or infrastructure provider, subject to winning spectrum in the short-term market.

In this case, the value attached to the spectrum lot would be higher for the player P2, as compared to player P1.

5.3.3 Case 3: Unequal valuation

In a real auction scenario, it is reasonably possible that the two existing players value a spectrum lot differently. Usually in case of auctions conducted, if two players are of the same type (discussed above), they would attach the same value to gaining a given lot or losing it. However, there can be some exceptions:

- The spectrum lot is contiguous to one of the player's currently owned spectrum. In this case, the valuation would be higher, if the player is able to access the lot for a reasonably long period of time[2].
- If one of the player owns unused equipment that works best with the frequency available in the current spectrum lot.
- One of the players has a strategic reason to gain the spectrum lot such as a prior trading agreement with another market player etc.

The payoffs for players P1 and P2 can be summarised as below:

- Winning the auction is equivalent to +7 payoff for P1 and +5 for P2
- Tokens cost for appearing in 1 auction is equivalent to -1 payoff
- Losing the auction in this case would be equivalent to -2 payoff for P1 and 0 for P2
- Penalty cost if price exceeds equivalent to -2 payoff for both players (same as before)

Rationale for payoff values: The payoff for P1 is chosen to be higher than nominal (i.e. +5) as P1 desires the lot more. The payoff for P2 is chosen to be nominal as before. This means that the loss of this particular lot might be disappointing to P1 in the same proportion i.e. by a factor of 2. Other factors remain the same as before. As both players are of the same size and type, the assumption is that the probability of winning the auction is 0.5.

The individual payoffs are different:

- Only P1 opts out – payoff for P1 is -2 (loss of desired spectrum lot), payoff for P2 is +5

[2]Some advantages of owning larger blocks of contiguous frequencies are higher speeds and higher capacity, in addition to providing network efficiency and cost benefits during deployment

- Only P2 opts out – payoff for P1 is 7 (gaining desired spectrum lot), payoff for P2 is 0
- If both P1 and P2 opt out — payoff for P1 is -2 (loss of desired spectrum lot), payoff for P2 is 0
- If both P1 and P2 participate — payoff for P1 is $(+7 \times 0.5) - 1 = 2.5$, payoff for P2 is $(+5 \times 0.5) - 1 = 1.5$

This still doesn't present a clear picture of the overall gains and losses because it presents an optimistic picture that the P1 has to participate. Recall that P1 also loses heavily in case it loses in the auction, which also has to be taken into account In this case, a tree diagram is more useful. This is represented in Figure 5.2. player P1 can now figure out the payoffs, assuming a 0.5 probability of win and loss at each stage to determine the overall strategy to play. This is still a zero-sum game, though of the extensive form type. This type of unequal valuation is also applicable, when the players are of the same type but one of them e.g. P1 wins less at the medium-term access stage. This means that P1 now needs to win the spectrum more at the short-term access auction, automatically increasing its valuation and hence payoff during this stage. The snapshot provided by tree diagram shows that tokens can be used as a oversight mechanism to manage anti-competitive behaviour under different scenarios.

5.4 Managing uneven players

Up to this point, the discussion has been focused on a two-player market where both the players are of the same type i.e. both incumbents with similar market cap, similar revenues, similar value of spectrum acquired during long and medium-term access periods. In case 5.4.3, a modified version was introduced where one of the players does not manage to secure enough spectrum during the longer-term access periods and hence the valuation (payoff) of the spectrum lot increases during the short-term access period increases, all other factors remaining the same. The case showed that in such a case only the individual valuation of the spectrum lot changes – how the players are affected when the lot is won or lost.

In this section, the case is modified by introducing players of unequal size, one incumbent and one new entrant. Incidentally, this would be the original new entry game – new player entering the market and deciding its options based on the decision made by the incumbent. A key focus of the BYOS framework is to reduce the entry barriers during the short-term access period. This means that the decision of the new entrant to enter the market should ideally be

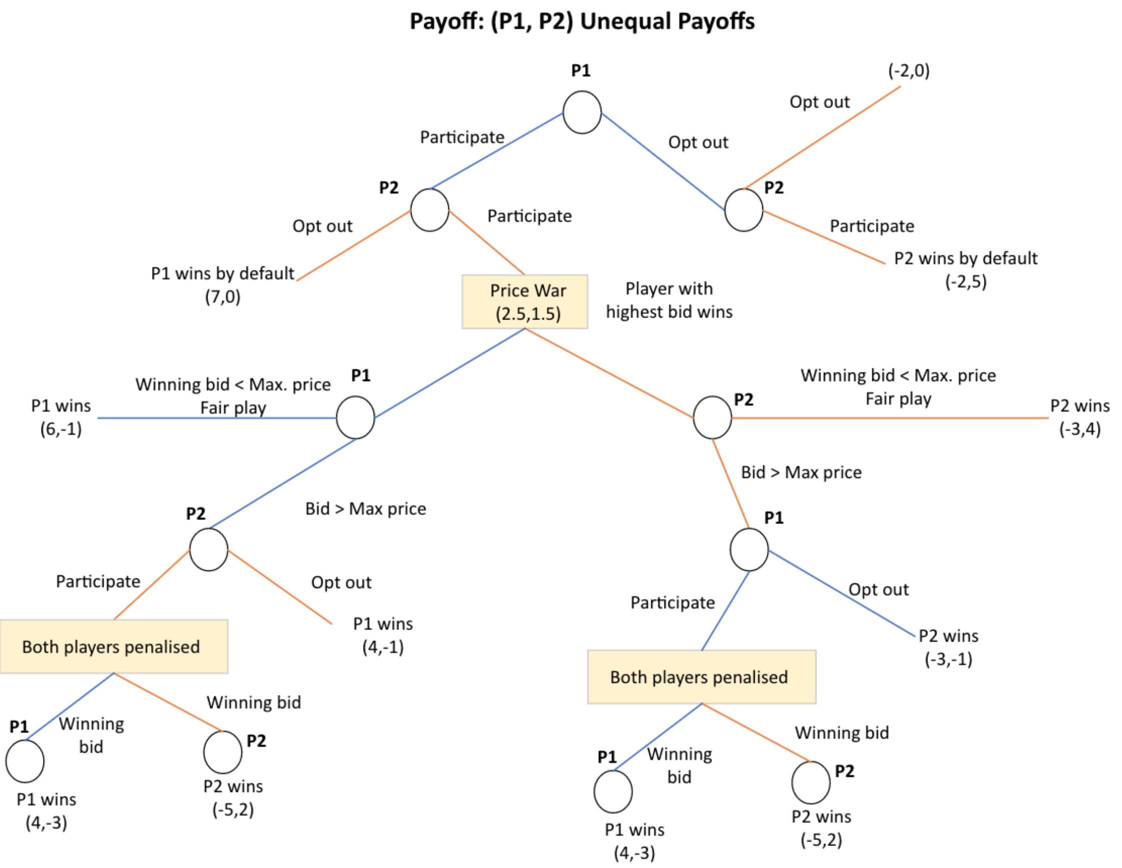

Fig. 5.2 Tree diagram of a simple auction with unequal payoffs using tokens
Blue lines: Actions of P1, Orange lines: Actions of P2

independent of the decision made by the incumbent. The purpose of tokens is to encourage the entry of smaller players in the short-term market, indirectly without mechanisms such as locking out spectrum deliberately from incumbents.

In the simplified system there are 2-buyers and a single seller in the market. The seller has a single indivisible product i.e. spectrum permit, to sell. Only one of the buyers is able to win the permit at a single auction i.e. this is a zero-sum game, like all the cases discussed earlier. Instead of multiple period auctions, the system is limited to 8-hour auctions. This means each day 3 auctions are conducted to sell the permit. The winning bidder get the permit for 8 hours, until it expires in time for the next auction. It is assumed that the time period between period of expiry, re-auction of the permit and re-issue of the permit to the new bidder (including the time required to affect the technical changes) are negligible. Extending this to a 1-week scenario leads to a total of 21 auctions to obtain spectrum permits for the entire period (i.e. 168 hours).

The new entrant at this point has no spectrum permits and intends to provide competitive services using only the spectrum acquired in the short-term. If it is assumed that this is the only way in which spectrum permits can be obtained (i.e. single-seller market), this means that the new entrant P_{New} i.e. P1 would require to win the spectrum permits for at least 50% of the entire period i.e. 84 hours. This translates into winning at least 12 of the 21 auctions (zero-sum game). The incumbent player P_{Inc} i.e. P2 has already won spectrum permits at the long- and medium-term auctions. While the short-term auctions would give capacity benefits, there is no pressing need to put extra effort into winning the auction. However, the incumbent intends to keep the new entrant away from the market or at least ensure that the new entrant obtains the permits with unfavourable conditions – higher than necessary and incurring penalty in terms of tokens used. Not being able to participate in the auction would be an undesirable condition for the incumbent as the new entrant is able to win spectrum permits by default, and at the reserve price set by the seller.

One of the capabilities of this framework is to be able to detect and manage anti-competitive behaviour, so that the market behaves competitively. This is done by managing the size of token buckets for each player. In this case, the token bucket size of the new entrant is P1 and the token bucket size of the incumbent is P2, representing the number of tokens each player has. The sizes of the bucket are independent of each other. However, there are some factors taken into consideration when the initial bucket is allocated such as the company size and the spectrum permits already owned. Company size is in turn a function of market cap and revenue. Hence, the bucket size of each player can be given as below:

$$For P1 : B_{New} = F_{New}(Marketcap_{New}, Revenue_{New}, No.of spectrumpermits_{New})$$

$$For P2 : B_{Inc} = F_{Inc}(Marketcap_{Inc}, Revenue_{Inc}, No.of spectrumpermits_{Inc})$$

Also assume that the incumbent player P2 is 10 times the size of the new entrant P1 and, as mentioned, P1's spectrum holding at the start of the 7-day period is 0. As a regulator, tokens have to be assigned to each player to ensure that the new entrant has a chance to competitively acquire the spectrum at least 50% of the given period. The comparative size of the incumbent and its relative strong position while winning the auction means that the only way it "loses" an auction is when it decides to opt out of the competition. The incumbent has financial reserve to absorb the cost of these decisions i.e. the company has financial resources to pay for any wins in the market at higher costs.

In this exercise, the scenario of different sizes of token buckets for each player was discussed. Not every distribution ends in a competitive market – the aim of the exercise. The purpose is to determine the maximum size of bucket for each player, during this period, to ensure that there is a fair competition between the 2 players. This is represented by different cases.

5.4.1 Case a: Bucket size is equal for P1 and P2

We start the exercise by assuming that both the players have equal number of tokens. The purpose is to determine the maximum size of the bucket. This means allowing both players to participate in all auctions: $B_{New} = 21, B_{Inc} = 21$

This scenario is depicted in Figure 5.3. As can be seen, even assuming the best case scenario where the new entrant wins all the auctions it participates, the incumbent will ensure that the prices are high enough to trigger a penalty. This means, the new entrant is able to win spectrum rights for 48 hours maximum (at the discretion of the incumbent). There is no game or competitive utilities here as the focus of one of the players, is simply to ensure that either the other player doesn't win or wins at unfavourable conditions.

5.4.2 Case b: $B_{New} = 21, B_{Inc} = 17$

The obvious solution is to reduce the number of tokens of the incumbent. This is done to ensure that the incumbent also has an incentive, not to participate in an auction or also has the

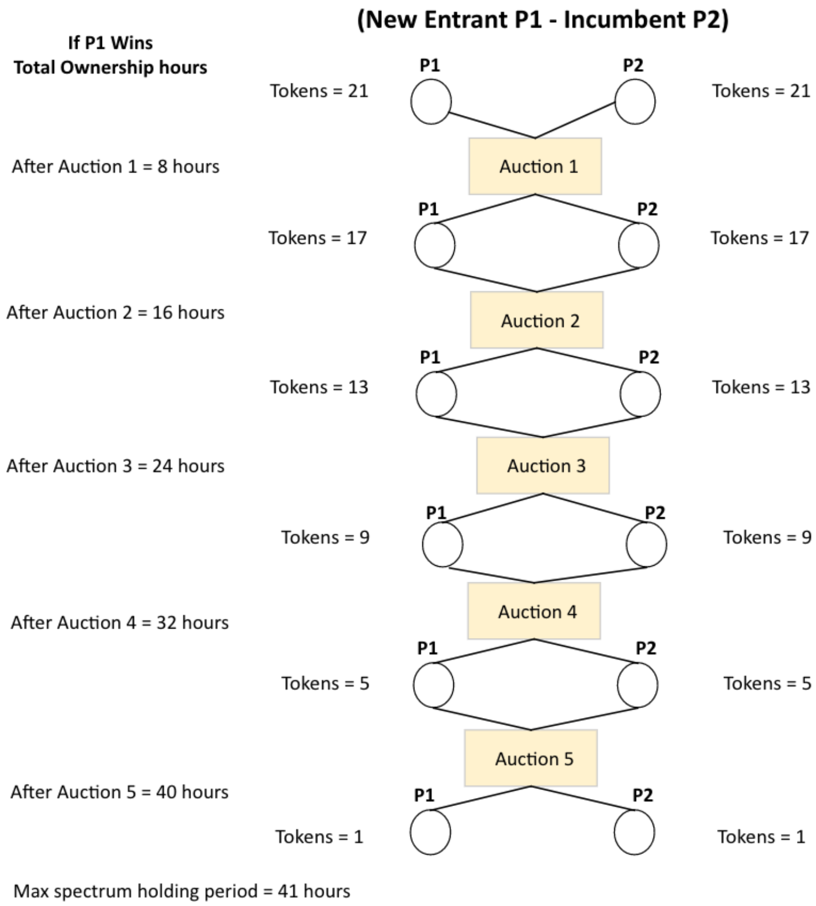

Fig. 5.3 Case a: $B_{New} = 21, B_{Inc} = 21$

incentive to participate fairly in the auction. As the incumbent has enough financial resources, the way to ensure this is by managing (reducing) the initial bucket size of the incumbent.

In this exercise, the tokens are successively reduced by 4. Every time a player participates anti-competitively in the market, they have to pay 4 tokens. For this exercise, it is assumed that the cost of auctions is 1, while the penalty is -3 for anti-competitive behaviour. The results are shown in Figure 5.4. The penalty could be -2 similar to previous cases. The results were same, but the process length was too long, so -3 is used as an illustrative case. Thus initial bucket sizes are: $B_{New} = 21 and B_{Inc} = 17$

Thus, reducing the initial bucket size of incumbent by 4 tokens is not sufficient.

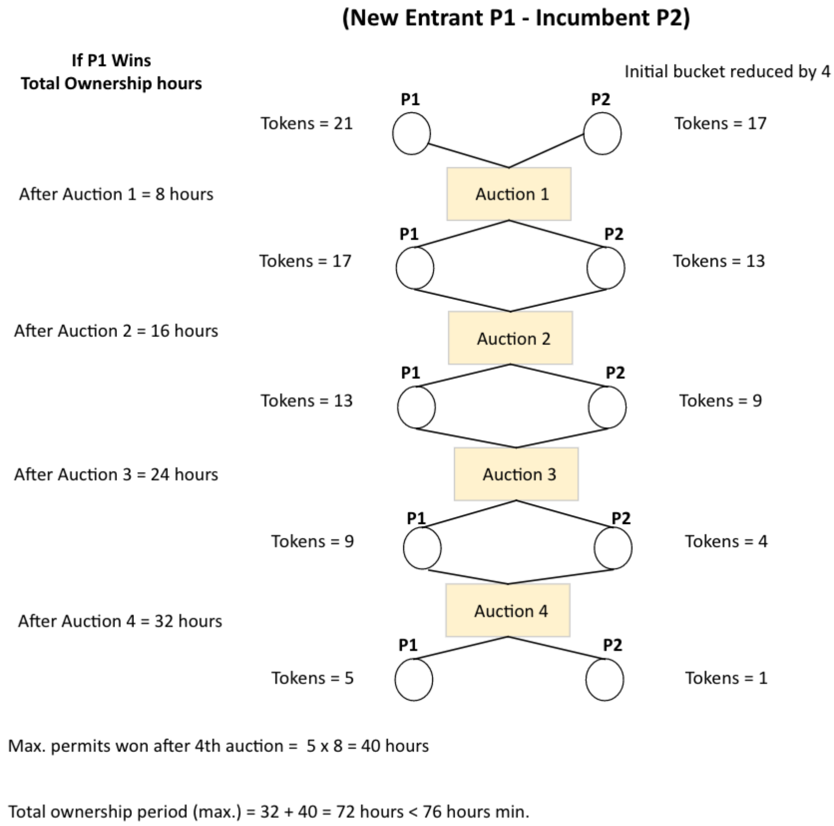

Fig. 5.4 Case b: $B_{New} = 21, B_{Inc} = 17$

5.4.3 Case c: $B_{New} = 21, B_{Inc} = 13$

The bucket size for the incumbent is further reduced by 4. This means $B_{New} = 21, B_{Inc} = 13$. At this stage, it can be seen that even when the incumbent loses all previous auctions (and pays the penalty), it still has sufficient tokens at the end to ensure that it wins 64-72 hours of spectrum permits, as shown in Figure 5.5, which is reasonably close to the minimum spectrum required.

At this point, the system starts to become somewhat strategy proof. This is because both incumbent and new entrant have the incentive to ensure that the other player bids above a required price – that would trigger the penalty condition for the other player. In case of a perfect information scenario i.e. both players know the exact price for triggering the penalty, this means waiting for the auctioneer to raise the price to this limit and ensure that the other player agrees to participate beyond this point. This means that prices for the first 3 auctions will always trigger the penalty rates. This obviously is not an ideal scenario, but note that the condition evaluated here is a case where one of the participant's strategy is to deliberately behave anti-competitively, because it can. The incumbent's utility has two parameters – to obtain spectrum and to force new entrant into loss-making decisions. The token bucket targets its ability to participate in auctions, to ensure fair competition.

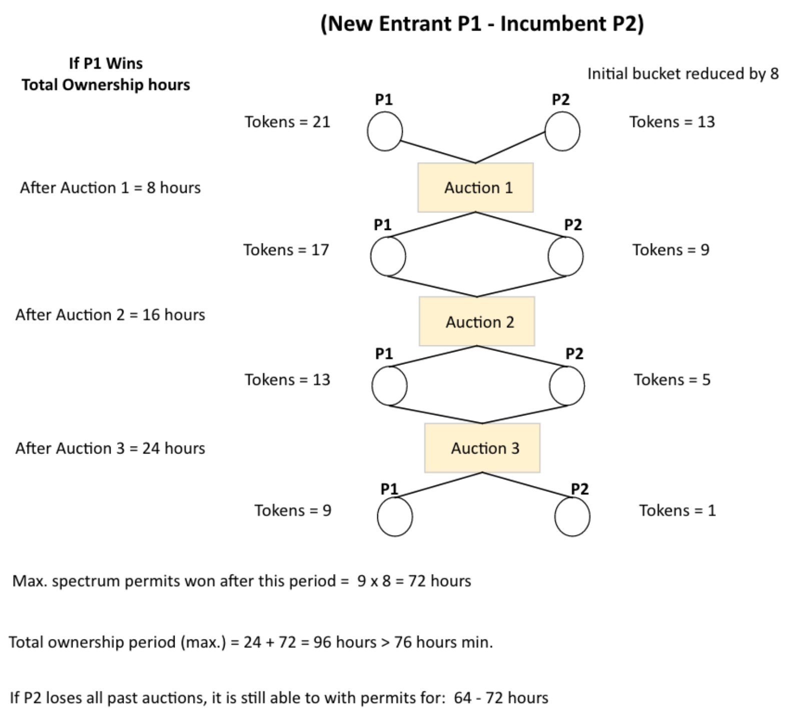

Fig. 5.5 Case c: $B_{New} = 21, B_{Inc} = 13$

5.5 Public safety agencies

Not all operators in the domain are commercial users. Spectrum users also extend to military/naval, aeronautical, deep space, and satellite communication areas. Most of these departments are given exclusive access to spectrum frequencies, because interference is strictly unacceptable. Military/naval communications are an anomaly as they require secure communications but have to be flexible in terms of communicating channels available within a given region. Interestingly, this requirement led to the active development of dynamic access technologies. Software defined radio (SDR) was initially developed to provide flexible communication channels for military radio. This software defined concept extended to cognition and was responsible for the next generation xG program and hence the beginning of xG Technology – the first commercial cognitive radio provider [190]. The requirements and advantages of commercial applications of cognitive radio and dynamic spectrum access technologies were very clear and have been the focus of a majority of the research done in this area. The previous cases in this chapter have discussed various aspects of competition management in this area.

In addition to the applications mentioned, there is yet another category that doesn't fit either of the categories described above – public safety communications. Before discussing the requirements of this type of communication, it is important to note that public safety agencies are not a single or even a homogenous unit. They comprise of several services that are built to help citizens such as law enforcement, fire and emergency medical services. Most of these work on legacy systems and in many countries, like the United States, the systems lack interoperability. Lack of interoperability is a key issue cited as a reason for promoting dynamic spectrum access schemes in this area [190, 191]. In addition to the lack of interoperability, the frequencies assigned to public safety agencies are also at times interleaved with frequencies designated for other commercial, transport (navigation) and non-military users. These users also lack interoperability with the public safety radio systems leading to problems in natural disaster or emergency situations (fire or active terrorism scenario) [191].

5.5.1 Suggested solutions

Researchers looking for solutions to the problems with public safety radio systems have actively discussed interoperability, which is one of the main applications of software defined and cognitive radio in this area [192]. Discussions concerning acquiring additional frequency in case of emergency situation is however mostly limited to spectrum pooling i.e. bundling all frequencies together to be used by different users as desired. This is theoretically a good solution, but impractical given the investment expectations of commercial operators. The technical solutions focus on public safety agencies sensing the existing radio environment and then using cognitive radio techniques to choose the best available channel for communication [193]. This is a good solution but, as research has shown, computationally intensive. Any emergency scenario would have all people reaching for their mobile phones. This means that the public safety radio systems would have to find space in a very busy and chaotic radio environment.

A better solution is if the radio frequencies are cleared, upon request, for the public safety radio systems in case of an emergency. This is the priority access, or "lights and sirens access" [193], referring to how flashing emergency lights provides emergency vehicles special permissions such as using any lanes, crossing red lights and requiring all vehicles to give way. Under this scheme public radio systems are given priority access in case of emergency. LTE has introduced priority access where users are divided into different classes that allows operators to restrict access to the radio network in case of high-load or congestion network. Users belonging to certain access classes can be barred from accessing full network services in case of high demand situation. This feature can be used to assign higher priority to public safety radios [192]. This is obviously another good system, but it also restricts the public safety radio systems to follow the LTE radio network and doesn't solve the interoperability issues.

5.5.2 Management using the proposed framework

In the proposed framework, public safety agencies can use the market system to flag urgent radio access requests. This converts the standard market into a seller's market. Selling the spectrum gives the advantage of higher prices for access (up to a pre-set threshold). An additional advantage could be that successful sellers are able to win back tokens – the only possible way of gaining additional tokens in the framework, apart from compensation for miscalculation.

Public service agencies can also opt for participating in the open market for purchasing access to spectrum. The "lights and siren scheme", mentioned above, is used to ensure that the agencies do not end up hoarding spectrum as follows:

- If the public safety agencies purchase spectrum in open market under standard conditions, then standard rules apply

- If the public safety agencies are able to demonstrate that this was an emergency situation, then they can regain all tokens for that particular transaction

The same two-buyer, one seller market are used as the previous cases. Here, both players are of the same size, but P1 is a public safety agency while P2 is a commercial operator. Because the public safety agency P1 would only enter the market if it needs spectrum, opt out is not considered as an initial condition. Following are the payoffs:

- Winning the auction is equivalent to +2 playoff for P1 and P2 in normal conditions
- In emergency condition, the payoff for P1 is +4. payoff for P2 remains unchanged at +2
- Cost (in terms of tokens) for participation in 1 auction is equivalent to -1 payoff for both P1 and P2, in normal conditions
- Penalty cost (in terms of tokens) is -2 payoff for both P1 and P2, in normal conditions
- In emergency condition, the penalty and participation cost for P1 is 0. payoff for P2 remains unchanged.
- In emergency condition, the payoff for losing the spectrum is -2

In normal conditions, if both players play fair, the payoffs are given in Table 5.7:

	P1 has the winning bid	**P1 has the winning bid**
P1 payoff	$+2-1=+1$	$0-1=-1$
P2 payoff	$0-1=-1$	$+2-1=+1$

Table 5.7 Step I – Fair auction, normal conditions

If both players start to bid aggressively and exceed the threshold prices (discussed previously), both players are considered to be in violation and incur extra token penalty (under standard conditions). This is shown in Table 5.8.

	P1 has the winning bid	**P2 has the winning bid**
P1 payoff	$+2-3=-1$	$0-3=-3$
P2 payoff	$0-3=-3$	$+2-3=-1$

Table 5.8 Step II – Auction with aggressive bidding, normal conditions

Similar to earlier discussion, if one player's bids exceeds the threshold the other player also has the option to concede. In this case, the player conceding does not incur the penalty cost, as shown in Table 5.9.

	P1 concedes, P2 wins	**P2 concedes, P1 wins**
P1 payoff	$0-1=-1$	$2-3=-1$
P2 payoff	$2-3=-1$	$0-1=-1$

Table 5.9 Step III – One player concedes, normal conditions

The conditions discussed above are the same as discussed previously. The payoffs change when there is a lights and sirens i.e. emergency condition. In this case, the emergency operator regains the tokens in future.

In emergency conditions, if both players play fair, the payoffs are as shown in Table 5.10.

	P1 has the winning bid	**P2 has the winning bid**
P1 payoff	$+4-0=4$	$-2-0=-2$
P2 payoff	$0-1=-1$	$+2-1=+1$

Table 5.10 Step I – Fair auction, emergency condition

In emergency conditions, if both players engage in aggressive bidding, the payoffs are as shown in Table 5.11.

	P1 has the winning bid	**P2 has the winning bid**
P1 payoff	$+4-0=4$	$-2-0=-2$
P2 payoff	$0-3=-3$	$+2-3=-1$

Table 5.11 Step II – Auction with aggressive bidding, emergency conditions

In emergency conditions, if one player concedes after the other player engages in aggressive bidding, the payoffs are are as shown in Table 5.12.

The tree diagram representing the situation is as shown in Figure 5.6. Similar to the previous tree diagrams, a snapshot of different scenarios is provided using the diagram. It again helps to demonstrate that, when rightly calibrated, tokens can be used as a means to automate competition processes during spectrum assignment.

The discussion above presents a way in which emergency services can be a part of the framework in a dynamic scenario. The emergency services enjoy priority based on situation, in a competition-free manner, but only if they are able to justify the situation as an emergency. Else, they are treated as other services in terms of payoffs and penalty. The model presented is a unique mode of treating emergency services in the telecommunications sector.

5.6 Valuations for different lengths of acquisition periods

The discussion is now moved away from the type of competitors, discussed in previous sections, and focus on the period of acquisition. Recall that in the previous chapter, different periods of acquisition for short-term auctions were given (though this discussion applies for medium-term access as well). Similar to the acquisition of contiguous bands discussed

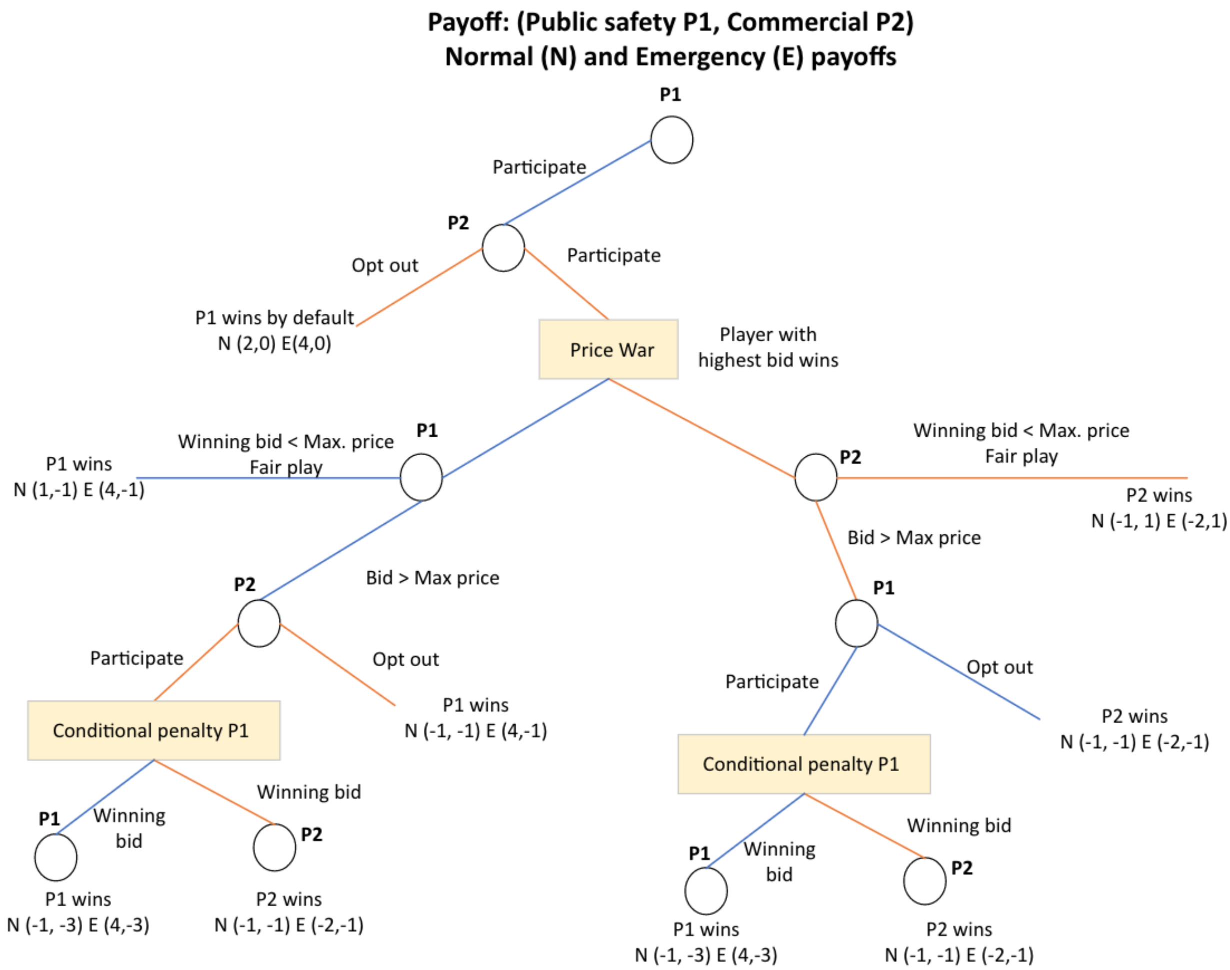

Fig. 5.6 Auction game between a commercial provider and a public safety agency
Blue lines: Actions of P1, Orange lines: Actions of P2

	P1 concedes, P2 wins	**P2 concedes, P1 wins**
P1 payoff	$-2-0=-2$	$4-0=4$
P2 payoff	$2-3=-1$	$0-1=-1$

Table 5.12 Step III – One player concedes, emergency conditions

in Section 5.4.3, the acquisition of spectrum for longer periods of time is also valued over shorter-term access. This is because the technical effort (processing power and time for retuning) required to re-authenticate and reassign channels is less if the spectrum permits are acquired for longer periods. The reason this wasn't discussed as a part of unequal payoff is because in this case the valuation for longer spectrum is in fact same for all players. All interested participants would ideally prefer to own spectrum permits for as long as possible. This also makes the auctions for longer term acquisition more competitive and logically the permits obtained would be more expensive. That would mean that auctions for shorter-term access now have lesser competition and the permits might be less expensive. This can be represented as below.

From Equation 5.1, N represents a finite set whose elements are called players. $N = \{1,2,\ldots,n\}$. In the present case, this is a set of all participants in the framework who are eligible to trade within the framework i.e. have sufficient tokens.

The auction can be one of several types – depending on the period of acquisition under offer. The types of auction are elements of the finite set $A = \{a_1,a_2,\ldots,a_y\}$, where each particular auction a_i represents auction conducted for obtaining spectrum rights for a period i. Each auction type represents a different period; no two auction types are of the same period. To simplify the discussion, exponential series is not considered, though as the previous chapters have mentioned,

$$Period\ of\ a_i = 2^i\ units\ of\ time$$

A subset of players $n_1 \subset N$ are interested buyers for auction type a_1. A seller r_1 is also taken from the same set $r_1 \in N$, but $r_1 \notin n_1$. This means that seller does not double as a buyer for the same auction. The seller has one indivisible unit for sale for this auction; the market clearing price (Walrasian equilibrium [194]) is C_1. Similarly, a subset of players $n_2 \subset N$ are interested buyers for some auction type a_2. A seller r_2 is also taken from the same set $r_2 \in N$, but $r_2 \notin n_1$, same as above. The seller has one indivisible unit for sale for this auction; the market clearing price (Walrasian equilibrium) is C_2.

The strategy part here is that one or more buyers and the seller involved in a_1 can also participate in a_2. The buyers involved in the auction might either actively participate (or not) and decide to try their luck at the next auction, while the same seller might decide to list further permits for offer for a shorter time period. However, the auctions themselves are independent. As a_1 and a_2 offer different periods of acquisitions, if period offered during $a_1 > a_2$, then logically more buyers would be interested in participating in the auction of type a_1 as compared to a_2. This means that competition would be higher during a_1 than a_2 and cost of the same lot of spectrum per unit also follows the same trend, i.e. $C_1 > C_2$

For a random buyer n_i from the auction a_1, the strategy S_{n_i} is given in Equation 5.2:

$$S_{n_i} = \begin{cases} \text{Participate} & \text{if } v_{n_i} \geq C_1 \\ \text{Opt out} & \text{Otherwise} \end{cases} \tag{5.2}$$

The valuation v_{n_i} is individual to each buyer and function of the infrastructure capabilities of the particular buyer as well as the standard financial factors. The Equation 5.2 means that, if the buyer decides that the valuation of the spectrum is lower than the price available for the lot (as a result of competition), then the buyer can participate in the next auction for a chance to win permits for a shorter period of time at a lower cost.

5.6.1 Setting up the scenario

To demonstrate this, a three-buyer one-seller scenario is used. Assume that there are only 2 auctions conducted during the day: the first auction offering spectrum permits for a 16-hour period and the second action (after the period of expiry of the permits from the first auction) offering spectrum permits for an 8-hour period. This means each day has 2 auctions covering the spectrum required for the whole 24 hour period. If the base period of acquisition is extended for a week, this means 14 total auctions to obtain spectrum permits for all hours (168 hours). In this case, it is assumed that a short-term access cycle period is 1 week – in the framework this period is actually 1-2 years.

The strategy space for each player is given by Equation 5.3

$$S_i = F_i(Tokens, Price, Penalty) \tag{5.3}$$

In an ideal scenario each player, P1, P2 and P3, would be able to obtain rights to an equal third of the time i.e. 56 hours. This is assuming that all players are of the same size and type. If this is the final goal, Table 5.13 shows the ways of achieving the permits for the desired period. It shows the tokens required (assuming fair play) for each option.

However, the goal of the framework is not to set up precise assignment distribution for the players in the market. The goal, instead, is to ensure that overall one or more players do

Strategy	No. of 16 hour auctions	No. of 8 hour auctions	No. of tokens needed
S_1	0	7	7
S_2	1	5	6
S_3	2	3	5
S_4	3	1	4

Table 5.13 Strategies for winning sufficient spectrum permits – 56 hours

not end up as a monopoly or use collusive or other anti-competitive measures against their opponents (either keeping them from buying resources or bid shilling). Monopoly in this case would refer to one of the players winning spectrum permits for more than two thirds of the time or greater than 112 hours. Table 5.14 shows the strategies of winning the permits for this period. It also shows the tokens required (assuming fair play) for each option.

Strategy	No. of 16 hour auctions	No. of 8 hour auctions	No. of tokens needed
S_1	0	14	14
S_2	1	12	13
S_3	2	10	12
S_4	3	8	11
S_5	4	6	10
S_6	5	4	9
S_7	6	2	8
S_8	7	0	7

Table 5.14 Strategies for winning sufficient spectrum permits – 112 hours

The first row shows that if a player only focuses on winning the 8-hour auctions, then they would require all 14 tokens to reach to a monopolistic stage. However, if a player decides to acquire permits for 16-hours, they can reach the monopolistic period within 7 auctions. This leaves the participant free to meddle with all other auction processes during this period by participating in an auction without an intent to buy. It is assumed that the players all play fairly in this case, which may not be true in real-life. However, this also means that the period of auction should be accounted for when tokens are assigned. This means the Option II, discussed in Chapter 4, is better for allocating tokens.

5.6.2 Discussion on strategy

The second element of the strategy space from Equation 5.3 is the price. This refers to the valuation if the spectrum was won at a lower or higher price. Thus, $Price = \{Low, High\}$. Price valuation is individual for each player. The last element of the strategy space from Equation 5.3 is the penalty. Penalty is incurred, if the players enter an aggressive bidding phase

With this background, payoffs are assumed as below:

- Winning a 16-hour auction has a payoff of +6, for P1, P2 and P3; payoff for loss is 0.
- Winning an 8-hour auction has a payoff of +4, for P1, P2 and P3; payoff for loss is 0.
- Aggressive bidding, triggering high price scrutiny incurs -2 payoff
- Active participation counted as -1 payoff
- Players consider winning below threshold price as +1 payoff, regardless of the auction type

As mentioned, the first auction conducted every day is for the longer period i.e. 16 hour auction. For this auction, the case that players P1 and P2 actively bid for the spectrum permit is presented. In this case, P3 would have two options – stay and fight or opt out and wait. The overall payoffs for each player is given in Table 5.15.

		P1 and P2 Participate			P1 wins Fair			P2 wins Fair			P1 wins Penalty			P2 wins Penalty		
P3	Opt out	-1	-1	0	6	-1	0	-1	6	0	3	-1	0	-1	3	0
	Participate	-1	-1	-1	6	-1	-1	-1	6	-1	3	-3	-3	-3	3	-3

Table 5.15 Payoff as a bi-matrix

In this type of a game, the strategies of the players cannot simply be an aggregation of a pure or mixed strategies. This is because the player has to evaluate the other player's strategy and respond appropriately. If a player, e.g. P3, chooses to observe P1 and P2 and then decide on the appropriate next step, then their strategy would be a reactive strategy. Reactive strategies do not exist for a one-shot game, but are common for extensive form games [195]. They provide a way of coordination between a group of players in repeated games.

One of the extreme forms of such a strategy is the Grim trigger, where the player cooperates for the first round of play and continues to cooperate so long as the other player(s) cooperate [195]. If the counterpart player does not cooperate, then the player defects and continues to defect until the game is over. This means P3 would continue, until the other players play fair. If P1 and/or P2 decide to play unfairly, then P1 defects. This is actually a good strategy to follow, because it would mean that P3 would avoid higher penalties in case there is aggressive bidding by the other two players. It is particularly helpful, if P3 is a smaller player or a new entrant. Because one of the other players definitely loses, the competition is automatically less for future auctions. Some other reactive strategies are tit-for-tat, where the player cooperates in the first round and then it does what the opponent (in this case one of the players) did in the previous round [195]. The P3 may logically choose the strategy of the winning player based on the outcome.

5.7 Summary of Chapter 5

In this chapter, games played for winning spectrum permits by different players were evaluated within the proposed framework. Different types of players were analysed, and their potential responses were evaluated. The discussion started with an evaluation of two players of same type and size (equal market capitalisation and revenue base). The purpose of the exercise was to present the method that can be used to design the mechanism of the framework. Even in this type of a situation, there is a situation for valid contention because spectrum is a valuable resource. Then, a discussion on uneven sized players was presented. This is a more realistic representation of the current market, given that the interest is move towards market-based scenarios to increase competition. The special case of public safety agencies is covered next. These agencies require priority access, but only during emergencies. Finally a discussion is presented on handling valuation changes due to different lengths of acquisition period. As spectrum is a scarce resource, the acquisition over longer period is more valuable to buyers. The discussion shows the flexibility of the framework as different types of competition scenarios can be addressed by simply altering the bucket size. This is one of the very first works to consider multi-period auction related games.

The limitation of this exercise is of course the payoffs values assigned. While not random, these may not be the exact representation of the actual payoff values, especially the case where two different types of players (new entrant and incumbent) were analysed. However, the exercise gives an insight on how the process might continue and shows that tokens can be used to manage spectrum assignment in a hands-off manner. A potential future work related to this chapter is extending the example discussed in 5.6 to continue for all interactions and possibilities by way of a live experiment using real players. The extended game would provide insights on the limits on token usage and how the process can be tuned further. In the Chapter 6, ways in which the BYOS framework can be implemented are discussed.

Chapter 6

Implementation plans

This chapter presents a discussion on the methods of implementing the architecture. As one of the key features of the framework is automation, with a view towards self-regulation, distributed ledger technologies seem the logical choice. The discussion starts with the use of digital platforms in general and before moving towards the different types of distributed ledger technologies. Following this, the architecture of the framework is depicted using one of the shortlisted technologies. Sample contracts and code blocks are also depicted to show how the framework can be implemented using distributed ledger technology.

6.1 Implementation using digital platforms

One of the main features of the proposed framework is that it is automated and has sufficient checks to ensure that regulators can have reports on market behaviour at any given point without actively intervening in the process. In this and the subsequent sections, we discuss the design of the automated platform itself.

From an economic viewpoint, platforms essentially act as a mediator of transactions in a two-sided market [196]. A market itself would be an economic platform whose owner sets a price for the buyers and sellers in a way that the benefit for one type of user (e.g. seller) would increase as the participation of the other type of user (e.g. buyer increases). Examples of popular digital market platforms are eBay, Amazon, Coinbase, Fidelity, eTrade etc.

Since its inception, digital platforms have transformed business and industry by revolutionising the way tasks are performed and hence the way value is created and recorded. Job descriptions have changed as have the trust relationships between different parties in the ecosystem. Prior to digital platforms, manual operators were solely in charge of entry to a system. They performed checks to confirm the identity of entrants and then cross-checked the status of entrants to verify their specific entitlements once they entered the system. This was the standard process whether the system was a restaurant, a shop, a bank or the stock market. Instant single-point entry and verification of entitlements was a privilege that was subjectively issued to either high-value patrons or parties with long-standing associations with one or more manual operators. With the advent of digital platforms, the system check-in process became faster, more efficient, more transparent and served as a bridge to the system inside rather than a gatekeeper. This meant more trust in the system in addition to faster operational times, facilitating more users and hence adding more value to the ecosystem.

This is the type of system we foresee for the mobile telecommunications spectrum market. Automated processes combined with seamless choice and subsequent integration between heterogenous network and infrastructure would serve to lower entry barriers. As we have seen, one of the key issues with bureaucratic control of spectrum assignment is that more spectrum remains unsold. This was a necessity in the past given the technological barriers. However, with the successful introduction of technologies like software defined radio and cognitive radio sensing, there is a need to shift the assignment landscape to a more flexible format.

When parties interact in a transaction, they often use mutually expected systems and objects, once trust is established[196]. These objects provide constructed arrangement using which participants form mutually agreeable forms of collaborations, and are known as boundary objects. These digital boundary objects are available to all registered users of a platform for free and act as the physical bridge between transacting parties. Several types of software platforms have been developed that make use of these boundary resources to transform traditional ways of doing transactions or business. Common types of digital boundary objects required to facilitate interaction between different actors in a transaction are [196] :

- Repositories such as a database or library that contain shared definitions and values needed to negotiate the interactions such as price setting or contract expectations
- Ideals such as diagrams or simulations used to represent the ideas without the use of word descriptions
- Coincident boundaries such as Gantt charts, roadmaps, timelines etc. that can be used by the parties to indicate the use of a shared/common resource or clarify mutual dependencies.
- Standardised forms such as forms and other related documentation that are used to collect, aggregate and transfer the data between the parties involved in transactions.

One such potential technology available to automate processes and create trust relationships without a central authority, is distributed ledger technology, such as *blockchain*. In the next two sections we provide a brief illustration on how the BYOS framework can be implemented using blockchain based smart contracts. This section provides an abridged description of the necessary background and features of the blockchain and smart contracts, while the next section presents an illustration of how the process would look.

6.1.1 Distributed ledger technology

Distributed ledger technology (DLT), as the name suggests, is a network of geographically distributed nodes using which an archive of shared, replicated, and synchronised data is maintained [197]. Traditional ledgers have a single centralised administrator or hub, through which all data flows, as it is controlled and validated – like the gatekeeper analogy mentioned above. In contrast, distributed ledgers have a network of synchronised databases that provide an auditable history of information, which is visible to any participant node in the network. To ensure data validity, DLT requires consensus from the nodes. Distributed ledgers can be public i.e. open to all or private i.e. invitation only [198]. In public ledgers the role of the network administration is shared by all participants, where the process of decision making, and validation take place using pre-approved mechanisms like proof-of-work or proof-of-stake. They are at one end of the continuum for managed databases, the other end being the traditional hub-type centralised databases [199]. Somewhere in the middle are private blockchains where certain roles such as entry is managed by a network administrator, but there is freedom when the approved nodes wish to interact each other.

There are several ways in which the ledgers can be stored and represented, which defines the different types of distributed ledger technologies. A brief survey into the multiple types of distributed ledgers was conducted to select a potential technology for implementing the BYOS framework [197, 200, 198]. Following are the better-known distributed ledger technologies:

- Blockchain – Blockchain is the best known and most popular among the distributed ledger technologies, to the extent that it is actually synonymous with DLTs. As the name suggests, transaction records in a blockchain are kept as a sequential chain of 'blocks' i.e. information chunks. Each transaction blocks contains the time stamp, the transaction details, encrypted sender's information and a unique ID called a hash function. This hash function is unique for each block and helps to characterise individual transaction blocks on the ledger.

- Hashgraph – In this type of DLT, multiple transactions can be stored on the ledger for each time stamp. Unlike blockchain, the transactions are stored in a parallel structure and each record is known as an 'event'. Again, as opposed to blockchain each node does not need to keep a complete record of all information. Nodes get the required information, update the changes and then discard the transaction, making the ledgers smaller in size.

- Directed Acrylic Graph (DAG) – This type of distributed ledger is similar to blockchain in many ways. The key difference is the consensus mechanism, which is quite advanced and scalable.

- Holochain – This distributed ledger is different because it is agent-centric instead of data-centric. There is no need for a global consensus protocol and every agent has their very own distributed ledger and communicates through their own unique signature. However, the ledger revolves around a specific set of values called the DNA, which ensures that any node trying to add new information on the public ledger is validated.

- Tempo (Radix) – This distributed ledger preserves the sequence of information like the blockchain. In Tempo, any node can opt to carry a subset of the full global ledger (called a shard). Every node carrying a shard gets a unique identifier (ID) for their subset of the ledger. Validation is done using logical clocks i.e. instead of carrying the actual timestamp, the nodes carry sequence of events

While there are pros and cons to each of the technologies discussed above, we selected the popular Blockchain technology for developing our framework. The main reason as the sheer amount of operational areas already successfully modelled using the platform, which gives a helpful starting point for implementing the framework.

6.1.2 Blockchain

Blockchain is a type of distributed ledger technology where transaction records are stored in a ledger as a sequence of blocks that can be independently added to any member of a network, known as a node. The blocks thus represent a list of sequential records and are linked to each other via a reference hash belonging to the previous block. The first block is called the genesis block, while each previous block is a parent block to the subsequent block. Each individual block comprises of two parts – header and body. Header has information such as version, hash of the previous block, hash value of the current block, timestamp, nonce, blockchain address of the block creator etc. Body of the block contains the actual transaction data and the transaction counter showing the number of transactions in the block. [201]

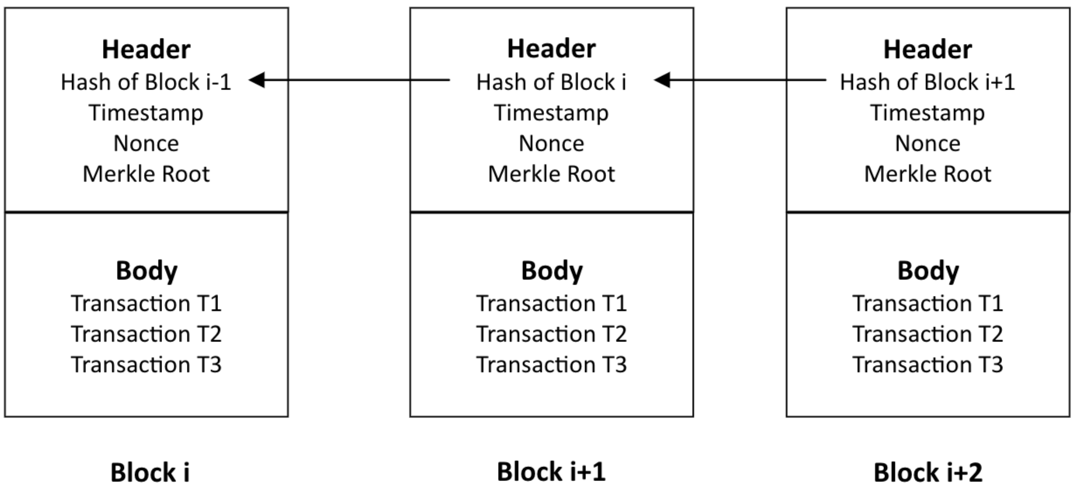

Fig. 6.1 Blocks in a blockchain[202]

All nodes in a blockchain have exactly the same privileges though their functions and degree of participation might differ. A new block and the transactions within are not automatically added to a network; there is a delay until they are collectively declared to be acceptable and transferred to ledger at which point it becomes immutable. This type of decentralisation is achieved in blockchain by means of consensus algorithms. Consensus algorithm is the manner in which nodes collectively decide on the validity of a block and the transactions contained within it. This generally works like a democracy – if a majority of nodes agree, then the block is added to the chain and the states of all nodes on the network are updated accordingly. The characterisation of "majority" and "measure of agreement" is what defines a consensus algorithm. As expected, and similar to a democracy, achieving consensus in a blockchain is challenging and is a subject of study by several researchers. A discussion on specific requirements and multiple implied properties of consensus mechanisms is out of the scope of this work at present. The two best-known consensus algorithms are Proof-of-work (PoW) used by the current version of Ethereum (i.e. Homestead) and Proof-of-stake (PoS) using by the new version of Ethereum (i.e. Serenity) [203, 201, 202].

In addition to decentralisation, achieved by consensus algorithm, two other key properties responsible for the widespread acclaim blockchain are as follows [201, 202, 204]:

- Transparency – The interesting thing about blockchain is that transparency is achieved without compromising the identity of the block owners. The owners have their identity information cryptographically hidden, but the transactions are publicly visible. This adds the feature of accountability that is missing from bureaucratic institutions.
- Immutability – The other important property of blockchain is immutability. This means if some information has been entered into the blockchain, it cannot be tampered with. This is important because the data cannot be played around to balance the columns and provides a true picture of the transaction history and present status.

6.1.3 Smart contract, Ethereum and Enterprise Ethereum

Blockchains have several applications – governance, auditing, file storage and data management, crowdfunding, sharing economy type services, identity management, anti-money laundering schemes, even stock trading and Internet of Things (IoT) [204]. However, the application that is of most interest to this work is the smart contract. Smart contract, also known as a self-executing contract, is a digital transaction protocol that executes the rules and policy of a contract. The protocol itself is a computer code that is deployed in a blockchain node. As smart contracts are executed over a decentralised ledger, they do not require middlemen and offer a transparent and conflict-free way to exchange goods and services. In addition to defining the rules and penalties, smart contracts also automatically enforce obligations without requiring the services of a third party. The execution happens in the ledger, meaning that once the trigger is activated, the code executes in near real-time across all the nodes forming the ledger network [205]. Smart contracts are well suited for auctions in particular because they can be applied to ensure that only the winning bidder pays for the auction, but other participants are marked to have taken part in the auction.

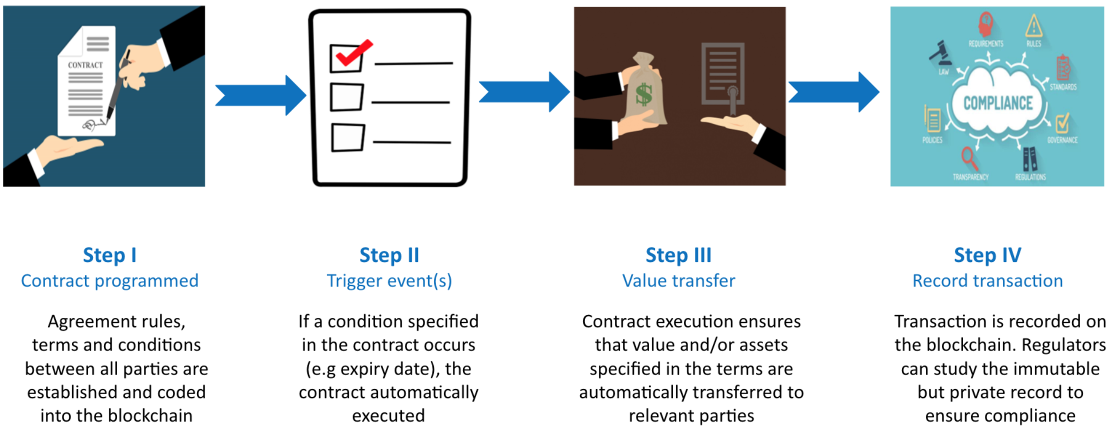

Fig. 6.2 Smart contract process [205]

Distributed ledgers such as blockchain, enable coding specific contracts between willing parties that auto-execute when pre-specified conditions are met. In fact, Ethereum, a popular open source blockchain project has been specifically developed for this purpose. In this network, the smart contract is created using Solidity or Viper – both high level programming languages. The code is then compiled, and then deployed and executed on the Ethereum blockchain. A smart contract code function can trigger other smart contracts, if required. However, each contract itself is very simple and computationally intensive routines are not preferred as the execution itself incurs a cost. [202]

6.2 Decentralisation in radio networks and spectrum assignment

Wireless networks in the past decade have experienced unprecedented growth, leading to several new technologies being tested and deployed. The future demand for wireless services in terms of scale, speed and quality of access is also expected to be immense. Managing the demand in light of ubiquitous connectivity would be a strain on traditional radio access networks. A logical solution to the problem is decentralisation as it reduces burden on a single central network and allows a large number of devices to connect without compromising on speed and quality of access. Because the network is no longer dependent on a central network, the processing power is lower, which means the cost of access would be lower.

Blockchain is one of the best-known solutions for decentralised networks and has been proposed for developing applications across many industries like finance, healthcare, government, tourism, supply chain and manufacturing etc. Blockchain's potential can also apply to mobile communications in several ways. At the 2018 Mobile World Congress, blockchain was proposed as a tentative solution by the FCC to enable 6G. Some potential application areas of blockchain in mobile communications is as an enabler for IoT, smart cities, micro-grids and small-cell services, edge computing, vehicular access network and wireless spectrum management [206, 207].

The use of blockchain to manage spectrum has been explored from multiple perspectives. In their work Dai et. al. [208] integrate artificial intelligence and blockchain to propose a intelligent architecture for the next generation of network. This architecture combines four types of wireless resource management schemes – spectrum sharing, content caching, energy trading and computation offloading. Consortium blockchain combined with artificial intelligence is proposed for maximizing caching resource utility. Their work mostly focused on caching-based solutions. Kotobi and Bilen [209] presented an auction mechanism for spectrum assignment using blockchain, where a virtual currency Specoins were introduced to pay for access to the spectrum. The mining process is very similar to Bitcoins. The focus of the model is on selling unused spectrum by primary users for available time slots. A few other works have used blockchain and smart contract solutions to provide spectrum sensing as a service. In this line, interference management using blockchain was evaluated by El Gamal and El Gamal [210], for a linear interference network with cooperative transmission between the nodes. Ling et. al. [207] used blockchain to develop a large-scale self-organised radio access network without the traditional information-aware network centre. Instead of auctions, the market clearance follows the first-come-first-served rule.

A radical proposal in the direction of spectrum sharing is given by Di Pascale et. al. [211] In this proposed solution smart contract agreements are used by small-cell owners to turn each into a mobile network operator at the micro-cell level. The thought exercise, admittedly boundary pushing because it pushes sharing down from the base station level to end user level, discussed how blockchain can be used to design secure sharing agreements of this form. A more comprehensive model involving different forms of sharing has been discussed in the paper by Weiss et. al [212]. In this paper, both public and permissioned blockchains are explored to find solutions to different types of sharing:

- Primary sharing – Where all nodes have equal rights to spectrum either in a competitive manner e.g. in unlicensed bands or in a cooperative manner e.g. by way of secondary markets.
- Secondary sharing – Where a primary user or incumbent has unused spectrum that can be accessed either opportunistically or by means of cooperative sharing e.g. ASA/LSA agreements.

[212]

6.2.1 Proposed Model

We present an illustrative example of how the model can be implemented using blockchain. For our system, a hybrid blockchain such as Enterprise Ethereum [213, 214] would be suitable.

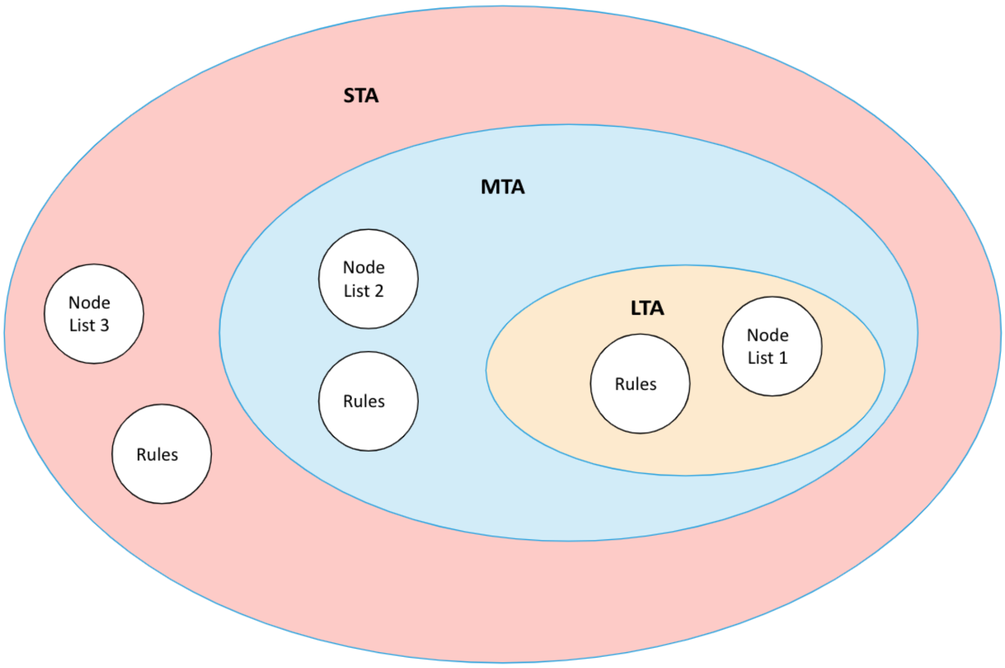

Fig. 6.3 Permissioned blockchain architecture for BYOS based on Quorum [215]

The main organization is set up as a permissioned blockchain, where the regulator acts as the authority letting only permitted operators to enter chain. The "permission" is similar to the mobile network operator or virtual network operator license, which can be granted in the system using a smart contract. On entry into the system, each operator is allotted tokens using one of the models discussed in Chapter 4. By definition, blockchain is a hierarchy-free architecture where all nodes have equal rights. Our architecture is hierarchical, but all members at each hierarchy have similar privileges. Using a combination of permissioned blockchain and number of tokens achieves this. Similar to Quorum, a system of three interconnected networks is created for each layer. This is shown below. As can be seen, each layer has invited list nodes. One of the nodes (usually the regulator) is designated as the administrative node, responsible for approving other nodes, sending invites and information about upcoming trades, arbitration, recording transaction data and updating/tracking tokens. Organisation nodes can participate at multiple levels, if they have permission. The number of nodes decreases for each inner level, showing higher hierarchy.

A recap of the description for each of the levels - STA, MTA and LTA - is given in Table 6.1.

Long-term access LTA	• Only incumbent MNOs allowed • 2^4 years (similar to current. auction periods) • Licenses offered by beauty contests to incumbent operators • License is accompanied by initial spectrum • Only admin fee is charged, there is no fee for spectrum
Medium-term access MTA	• Similar to present auctions • Multiple ownership periods: 2^3, 2^2, 2^1, 2^0 years • Incumbent MNOs, new entrant MNOs, even incumbent MVNOs can participate • License fee based on market prices • Ownership extended if demand remains the same

Short-term access STA	• All interested parties are allowed to participate • Ownership period does not roll over. New trade for new period based on current conditions. • Multiple ownership periods: 2^5, 2^4, 2^3, 2^2, 2^1, 2^0 weeks; 2^2, 2^1, 2^0 days; 2^4, 2^3, 2^2, 2^1, 2^0 hours. • Various forms of trading allowed, based on the discretion of the spectrum owner • Multiple ownership formats allowed • Prices set by owner based on current demand

Table 6.1 Recap of three levels of BYOS

The long-term and the medium-term layers in our framework occur infrequently and hence incur low operating overheads. As mentioned in the table above, the system theoretically organises trade opportunities every hour in short-term access period. The process is shown in the Figure 6.4.

The nodes within a region keep updating the local database about the latest demand and availability of spectrum channels. The designated admin node collects the information periodically (every hour) and sends invitation to all regional nodes regarding available opportunities within the region. At the same time, an auto-invitation is sent to all nodes for upcoming trades. All nodes are able to view the information and participate in the trade, if they have sufficient number of tokens. This can be done via a smart contract, similar to invited tenders for a project.

At this point, operators interested in viewing the trade respond to the call and this group is considered to be the initial group of buyers. Buyers are given the opportunity to change the quantity and period of auction at the given price. If sellers and buyers agree to the terms (and demand $\leq$ supply), tokens are collected, and spectrum is assigned. In this case, only the parties who have won the bid are considered to be an active part of the trade and are the only ones who pay the participation fee in terms of the tokens. If one or more buyers decide to purchase the spectrum on the same terms, such that demand exceeds supply, the price of the spectrum lot is raised, and the new price is sent to the buyers in the initial group (only) as a new smart contract. Once this happens, all buyers who respond to the invitation are considered to be active participants (final group) and pay for the transactions in terms of tokens. In this case, all buyers in the final group are required to pay the token regardless of whether they win the bid eventually or not. This ensures that the transaction fee is commensurate with the use of the network. If the auction extends beyond a certain period, the information is recorded with the regulator and all participants may be penalised, in terms of future token allotment or loss of tokens as discussed in Chapter 4.

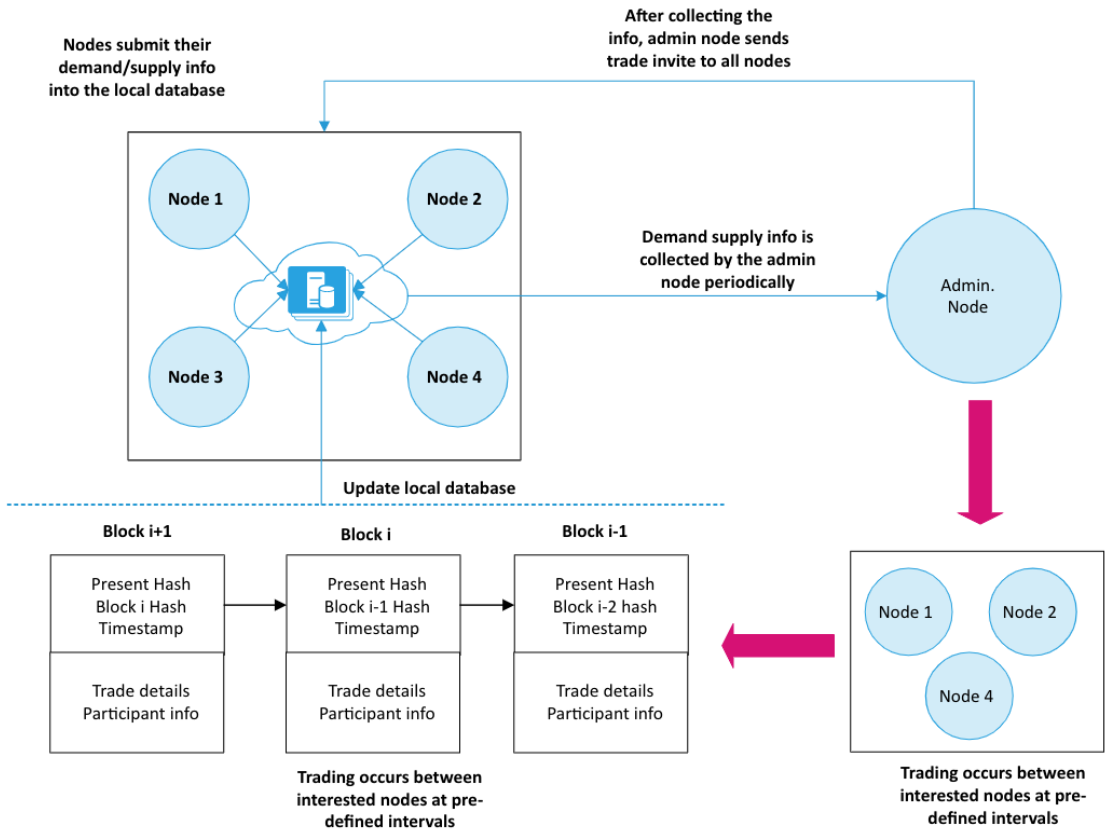

Fig. 6.4 Blockchain-based process for trading within a region

All information related to the trade is updated as part of a new block. While most of the information is public, some part can be encrypted for restricted viewing. Theoretically most nodes are permitted to view most of the information. To access restricted information, every private view is accessed via a call to the database, which in turn is recorded immutably on the chain. Types of information are illustrated below:

- Publicly visible – Information available to view freely can include items such as time stamp of the trade, quantity of spectrum traded (percentage acquisition), expiry period, region information, the price of the trade and the current owner of the spectrum.

- Semi-private (shared with regulator) – Information sent to the regulator includes tokens consumed, token balance, trade behaviour (undue influence or jacking up the price etc.), total spectrum owned within the region and overall etc.

- Private (internal or shared) – In addition to trading information provided above, trading parties may have other terms and conditions for instance details of spectrum usage in case of shared acquisition, which are specific operational details that companies may consider private or shared only with the trading partners for the particular trade.

Here we have consciously used the term 'trade' instead of auction. This because the framework is not based on any specific spectrum allotment mechanism, and regulators and/or operators are free to come to any form of trading that is approved by the regulator of a country. The information of the form of trade and trading terms are however public, ensuring transparency. In case of private trade between two or more individual operators, the voting mechanism can be decided by the regulator. Blockchain, such as Quorum, allows different nodes to be set as voters for validation.

6.2.2 Infrastructure access

For our framework, we assume that all the operators either own or have access to the infrastructure required for the last-mile RAN. In future, infrastructure access can also be sold as part of the same blockchain. Alternatively, infrastructure owners can set up their own blockchain to provide infrastructure-on-demand type service to interested operators. A potential way of using infrastructure and spectrum to provide services to users within a region is given by Weiss [212]. In their paper, they provide an example where a RAN provider provides automated and secure access to its infrastructure to RF devices by means of a smart contract. Here, requests from end users are gathered and matched to available base stations, which then collects and transfers the fees. A similar system can be used to match spectrum and infrastructure from multiple operators. This is shown in Figure 6.5.

In this case, operators with access to spectrum within a region but without access to necessary infrastructure, post their requests. The requests are gathered and matched to available base stations automatically. This can happen within a few hours, if there is availability. The spectrum and base station ownership is protected by an encrypted smart contract, which protects the privacy of the owners and hence overtly anti-competitive practices.

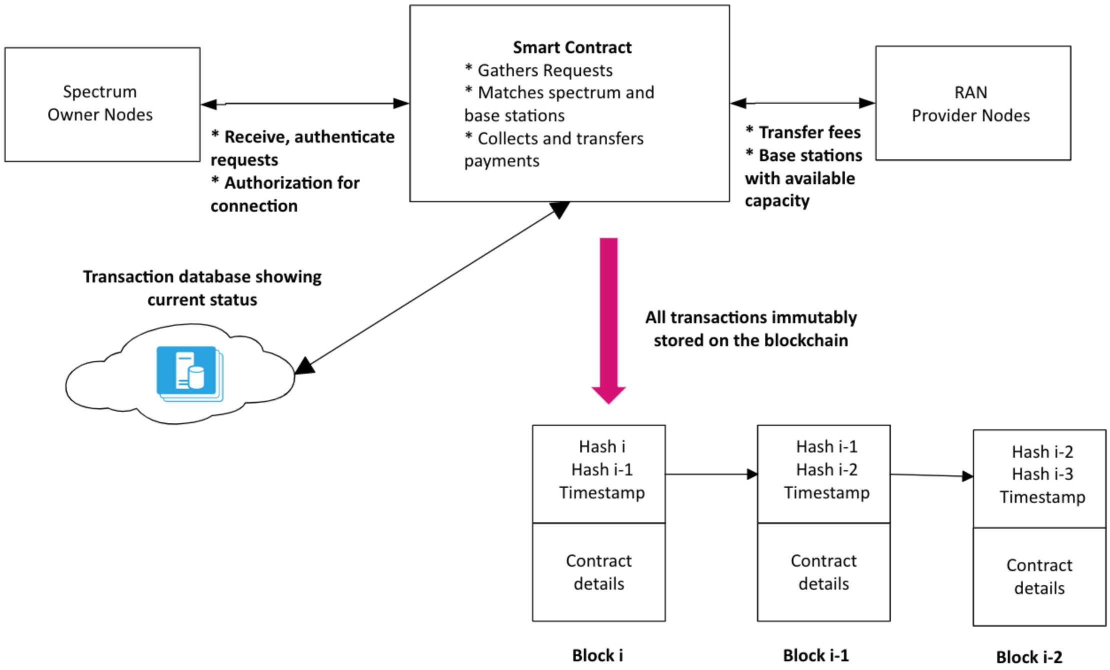

Fig. 6.5 Potential solution to match infrastructure to spectrum within a region

6.3 Sample dynamic spectrum access contract

In this example we provide an illustration of the different elements of a smart contract. Following the various cases discussed in previous chapter, we take the case of a contract (post-trading) created between an emergency service (Fire Services SA) and a private mobile company (Telephone Aus. Pty. Ltd.). The issuer has provided complete (though conditional) ownership of spectrum in the band 1745-1750 MHz. for 24 hours. Geographical areas for the licenses would be available in a separate register/code file (not shown here), containing HCIS identifiers[1] corresponding to location 4. They are a part of the centralised database shown in Figure 6.4, updated whenever a contract is created. The contract showing various elements of the agreement is given in Figure 6.6.

[1]Hierarchical cell identification scheme (HCIS) identifier means a unique identifier used to describe a geographic area in Australian Spectrum Map Grid (ASMG). An ASMG cell is a five minute of arc square cell and an ASMG block is a collection of cells. Each cell and block is assigned an HCIS identifier.

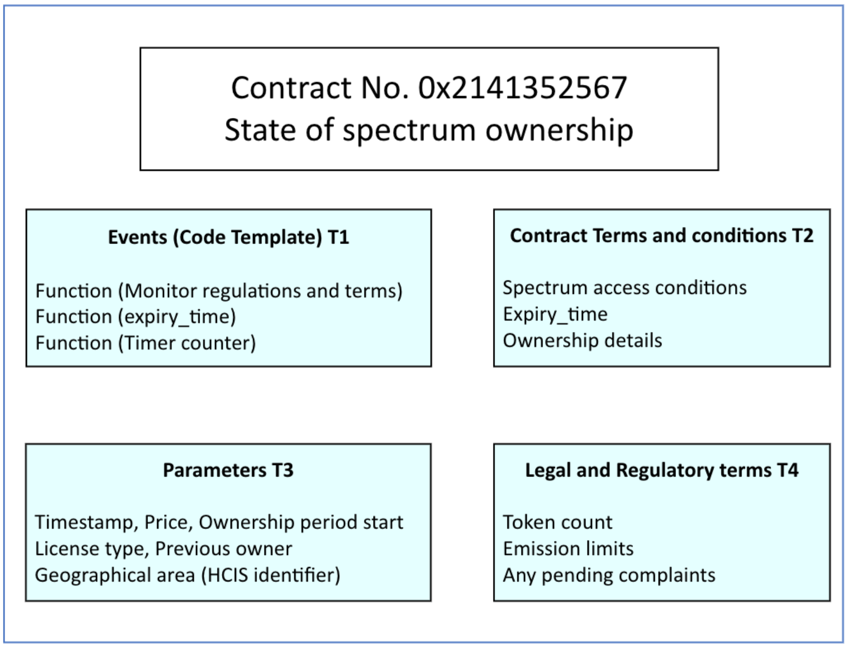

Fig. 6.6 A sample smart contract for BYOS

6.3.1 Explanation and details of various code blocks

The function block T1 is the main part of the contract. It says that the contracted buyer is obliged to follow both the Contract conditions T2 and the Regulations T4. This part of the contract monitors various conditions of the code and flags when any breach occurs or when the period of acquisition ends. The algorithm for T1 is given below

Algorithm 1 Monitor contract and legal terms till expiry period

```
procedure MONITOR(spectrum conditions, legal terms)
    Timer = expiry time − entry time          ▷ Define the value of timer counter
    while Timer ≠ 0 do                        ▷ Wait till permit period expires
        Timer = Timer − 1
        if A legal condition is breached then
            Flag to the owner and regulator
        end if
        if A spectrum condition is breached then
            Flag to the owner, concerned party and regulator
        end if
    end while
end procedure
```

As can be seen from the Algorithm 2, once the contract comes in force, a counter starts to track the expiry time, after which the spectrum is automatically freed up (and information sent to all parties in the blockchain regarding the availability of this spectrum). While the contract is in force, the Parameter block (T2) provides the details of the license. Users can determine the information that is available as part of the public ledger.

The monitoring function in Algorithm 1, uses the spectrum conditions listed in T3 to identify any potential breach.

Algorithm 2 Monitor spectrum conditions

$C = 0$ ▷ Set flag to 0 at the start
function MONITOR(*license conditions*)
  $C \leftarrow$ *license conditions*
  if Noise > Threshold **then** ▷ Threshold is defined in the license terms
    $C = 1$
    Return C ▷ Send flag to the owner and regulator
  end if
end function

Legal and regulatory function is defined by the regulator as per the laws and legislations of a country. In this context, a helpful tool is RegTech. Regulatory technology (RegTech) is a subset of Financial Technology (FinTech). The idea is a cloud-based scheme used by companies to check specific laws/policy/regulations are being followed. RegTech is a technology that makes use of IT in the context of regulatory monitoring, reporting and compliance. The technology emerged as a solution in response to the institutional demand arising from the exponential growth in compliance costs. The primary clients of RegTech are the financial industry, but the technology can be modified to any application area. As of now, many RegTech companies use the cloud through software-as-a-service to provide services to their clients. [216] However, smart contracts also allow the inclusion of RegTech (regulatory technology). RegTech or a similar technology can be used to codify T4 in a way that would allow spectrum regulators to maintain a close, but hands off oversight. Regulatory bodies can modify this by developing a version that must to be included with every contract in the landscape. This would automatically check the applicable regulations in the particular contract and generate an approval stamp. Else the contract can either be rejected or sent to the regulatory authority for review.

6.4 Are DLTs the only solution?

One of the discussion points that keeps coming up is whether discussion blockchain is needed at all or are there better ways to manage the system. Current alternatives to DLTs are a centralised database or a cloud-based system.

A centralised database is best for a single-point storage of information. However, this type of database has a key limitation that it does not allow shared write access [217]. This feature is required for our framework particularly when a private trade is conducted between two parties. Write access is not an absolute necessity of the system because the currently used system also supports third-party trading. In this case, trades beyond a certain threshold have to be scrutinised by the government. The change of ownership of spectrum and/or the related infrastructure should also be updated as soon as possible. However, we have found that this does not always happen. This also means that if, for instance, the information is found to be incorrect or dated, there is no immediate flag put on the document to inform of this status. Thus, there is a fair chance that the information available may not be correct. Hence, the main reasons to choose a distributed ledger technology over central database are efficiency, onus to update information (with auto-reminders and flags), transparency and immutability.

Prior to the advent of cloud-based storage, the storage was highly decentralised. Most organisations had their own servers and individuals used their own storage devices. These methods were expensive, unreliable and a lot of effort was put to ensure that backups systems were in place. Cloud-based storage has changed the mindset to trust third-parties with highly sensitive information. Though convenience in terms reliable uptime and seamless availability drowns most complaints, regulation around security and privacy of information is still sketchy. [218] This is the key drawback of switching to a cloud-based system for our type of system. The upside is that we require much of the information to be in the public domain, so privacy is not as much of a concern. However, the information on a cloud-based system is not immutable. Traditionally database entries on a cloud-based storage system are overwritten when new information is updated. Even when there are policies to ensure that such a thing does not happen, the possibility of erasure of data always existing. Also, as there is a single point update of information, lost data recovery is difficult. There have been efforts to build immutability into cloud-based system and some of them might even turn out to be good solutions. However, the ownership of information with the biggest (and not always the most trustworthy) companies of the world, is still a barrier to using cloud-based storage systems as an alternative to distributed ledger systems.

The advantages of distributed ledgers are many. However, it is not a solution to all multi-user systems and a decision to invest in the technology must be carefully evaluated. Following are the limitations of distributed ledger technologies:

- One of the key trends around distributed ledger technology is to consider the distributed nodes as a proof of immutability and security and hence as a solution to everything [219]. This point is indicator to the wider issue – a lack of understanding on what the key terms mean and how technology works – despite the hype the technology has generated.
- Continuing with the universal applicability expectation from DLTs, there is the idea that all industry processes need changing dramatically so that they are decentralised and distributed with no central authority [219]. Central authorities do have problems, but they vary across application areas and countries. As discussed in the initial part of this thesis, an in-depth understanding of the role of regulations and processes is required before deciding to decentralise it using blockchain.
- We also find that it is difficult to find governance solutions to blockchain technology. As the blockchain comprises of independent participants who all have the same hierarchy, it is difficult to set out the responsibilities and acceptable usage terms for participants. Some potential problems with governance are related to arbitration of disputes, methods of error correction in case a wrong data is appended to the database, assigning responsibility to maintain the integrity of the system etc [219]. While reviewing blockchain as a potential technology for our system, these were our main concerns. And hence, we opted for a permissioned blockchain system, which has the regulator acting as the administrator and entity for granting different levels of permission.
- Because of the immense interest in this area, several companies are working towards developing their own DLTs with unique features. The problem is that this would cause fragmentation. [219] While conducing our research in this area, one of the biggest challenges was to sort out the specific technology suitable to our system and find requisite application information on it. Technology is moving towards convergence and fragmentation would be a hindrance to this goal, especially if the multitude of systems have interoperability issues.

A lack of knowledge on how technology interacts with existing systems, which part of existing process should be decentralised, and fragmentation of platforms have all contributed to mass confusion around blockchain and a real picture of what it is capable of it difficult to obtain. Future work in this area is to undertake an in-depth survey on the platforms available and their respective advantages in building a hands-off, eyes-on type regulatory architecture around dynamic spectrum access.

6.5 Summary of Chapter 6

In this chapter, the issue of selecting a platform for automating the framework was discussed. Automation solutions until very recently focused on the question of which software to be selected. However. the development and rapid adoption of distributed ledger technology have provided a new method of automation by covering the function of regulators. The technology is still under development and there are multiple players in the market, making it harder to select a specific solution. Hence, the purpose of this chapter was to review the available distributed ledger technology in general and shortlist one for the development of the framework (Quorum). The chapter also discusses whether distributed technologies are the only solution for automating the proposed framework. Illustrative examples of system architecture using Quorum, sample contracts and code blocks are included to show how the framework can be implemented using a distributed ledger technology.

Chapter 7

Summary and future work

7.1 Core conclusions

As mentioned in the Preamble, this work started with the hypothesis that *"the widespread adoption of personal mobile radio technologies would soon lead to wireless spectrum scarcity"*. The first step taken was to test this hypothesis. The hypothesis was partially incorrect when multiple studies [18, 19, 21, 28–30] noted that the spectrum scarcity was used as a basis for ad-hoc assignment of spectrum policy in the early decades of spectrum assignment, especially in the US. However, the proliferation of devices and new technologies are still a strain on the existing assignments and more spectrum is required, as compared to what is currently available [128]. The research then split into two areas – evaluation and management of the affect of policy development on spectrum assignment (covered in Chapter 1); and understanding the requirements of newer technology and including this as part of a new framework for spectrum assignment (covered in Chapter 2).

The underlying research question, however, remains the same: **how to trade or share spectrum based on dynamic demand, without intervention from the regulator i.e. bilaterally**

To understand the impact of the effect of policy development on spectrum assignment, a systematic survey was conducted into past and present spectrum assignment over 32 countries. The countries included the major economies of the world and a sample of countries from different geographical regions. The causes behind inefficiency were found to be different in different countries. For instance, in the US the cause of inefficiency was fragmentation brought upon by cumulative effects of a history of ad-hoc assignment. In contrast, in Central and Eastern European, South Asian, African and South American countries, necessary bands identified for IMT services by ITU were either locked or were not licensed, despite being available for licensing. In western European countries, the assignment process had been measured and hence these countries had the most efficient and advanced assignment processes. However, it was found that in many countries, policies were imitated at key points during the history of telecommunications policy development. The study was expanded to understand the points at which other policies were imitated, the reasons behind the imitation, and the mechanism used for eventual adoption of the policies. The theory used to cover this is policy diffusion [25, 22]. Following conclusions can be drawn from the study:

- There was ample evidence that policies were imitated at specific points in telecommunications policy development history – Beginning of regulation in 1900s, liberalisation in 1980-1990s and choosing a competitive spectrum assignment mechanism in 1990s-2000s

- The success of policy imitation depends on whether the policy was adapted to local socio-economic and political conditions and whether various affected parties were consulted.

- Regulators are highly involved in every aspect of spectrum assignment – several countries have a major government operator, government acts as the seller and the trade regulator.

- Methods to encourage competition by regulators (spectrum caps, spectrum floors, spectrum/license set asides etc.) were ineffective as new operators often either merged with existing operators or went bankrupt.

- Licensing periods are getting longer. Regulatory push is to keep the current licenses intact till 2030s, while exploring GHz bands for newer technologies. The UK has been experimenting with infinite period licenses for existing operators.

- Exorbitant spectrum licensing fees raised during 3G spectrum assignment was initially considered a big success, then an eventual policy failure when many new entrants filed for bankruptcy, returned their spectrum to the regulator, or merged with larger operators.

- MNOs require long-term ownership to recoup investment costs because infrastructure is inextricably linked to radio spectrum licenses.

- The number of major MNOs for all countries under study remains between 3 and 5, despite efforts from governments to increase competition

- Newer models of licensing are being actively evaluated. Alternative ownership schemes such as ASA/LSA, SAS etc. have been successfully adopted by regulators in the US and Europe.

To understand the impact of technology on policy development, a background study of existing technologies and research was conducted. The purpose was to analyze the mechanisms used for spectrum sharing and assignment. Following are the key findings from the study:

- New technologies (e.g. LTE) are band extendable and support the use of multiple technologies in the same frequency bands
- Software defined networking has been adopted by operators to manage their capacity in real-time (e.g. self-organizing networks)
- A few operators have successfully made use of dynamic access principles to provide radio services (e.g. xG Technologies in the ISM band, Vanu Anywave)
- The newer technologies areas extend in both narrowband and broadband directions, each with their individual advantages and hence applications (e.g. UWB and UNB technologies)
- Software defined radio has been actively adopted, especially at base station level. Base stations are able to directly manage local capacity and sharing (eNodeB and the docitive base stations)

This concluded the literature survey-related contributions from the present work. The next section discusses the key contributions in terms of proposed framework achitecture and features.

7.2 Original contributions

The exhaustive survey of literature conclusively providing evidence of policy diffusion in the development of telecommunications policy is one of the key unique contributions of the work. This includes determination of types of mechanisms used for policy diffusion, analyzing universal and region-specific motivations for adoption, and causes of success and failure.

Using the results from this study, a framework was proposed for dynamic spectrum access (for trading and/or sharing). The architecture of the Bring Your Own Spectrum (BYOS) framework and its various features form the next set of original contributions arising from this work. These are listed below:

- Proposing a three-tiered, hierarchical framework that allows spectrum ownership for variable periods. Categorisation of types of owners is automatically coded in the framework, which decides privilege levels of each participant. A novel idea proposed here is quasi-static mode of spectrum assignment where trades occur over a exponential time frame. The framework is flexible, so that the time frames can be shortened or lengthened by the regulator, based on demand or policy constraints. This adaptability makes the framework flexible for different countries.

- Proposing a trading unit that uses interference as a means of assigning spectrum. Interference-based mechanisms are often considered difficult to quantise and hence apply. For this, a novel multi-highway based analogy was introduced to show different players and how they can coexist within the band under given constraints. The research does not negate previous works done on interference, but enhances them by bringing them under a common framework for assignment.

- Proposing a novel mechanism to ensure fair competition in spectrum markets – token, based on network traffic shaping concepts. In brief, a token gives a participant the right to participate in a trade. Tokens are consumed when participants enter into a trade. At this point, the thesis only considers monitoring buyer behaviour. As the current market is single-seller type, the seller being the government, monitoring the seller behaviour using tokens is not required at this stage. However, in a multi-seller market seller behaviour monitoring may also be required and the proposed mechanism can easily be extended to cover this requirement. This shows the flexibility of the proposed framework

- Illustrating the use of tokens in different competition scenarios such as those involving different operator types and different acquisition periods.

- Using smart contracts and distributed ledger technologies to present realistic implementation ideas for the framework.

7.3 Future work

In this thesis, a framework for spectrum assignment was presented that would allow more efficient spectrum assignment. A summary of the work done is presented in Section 7.1

and 7.2. This means that regulators are now able to move their focus away from the routine activities of spectrum assignment, having pre-specified the boundaries.

Technology limitations have made the spectrum assignment process challenging in the past, but the advent of software-defined radios and the possibility of introducing cognition in the infrastructure means that infrastructure and the last-mile radio access are not tightly bound and can be programmed as per demands. Using the BYOS framework, spectrum can be assigned flexibly all the while allowing MNOs have a chance to recover their investment costs.

The research presented an overview of the architecture and introduced mechanisms to manage competition. We are currently working on evaluating the competition mechanisms under different scenarios and for different types of operators. The purpose is to ensure that the system cannot be gamed, and the use of tokens automates the process of competition management. Limit conditions of assignments have not been evaluation, which is the next step.

The next step in software platform development is to build a working model for the assignment using blockchain. There are privacy and security concerns with blockchain that also need to be addressed, which is another avenue for future work in this area. The illustration of framework was limited to blockchain (specifically Enterprise ethereum); it is conceivable that another distributed ledger or software platform might suit the framework better. Hence, analytically assessing the most suitable type of distributed ledger is another potential direction of research.

At the present stage, we have limited the end users to be short-term operators. Ideally, the system should be extendable to at least a group of users sharing similar objectives (sharing similar geographical region), where they are able to change network operators at will, based on their demands. The concept of a pure cognitive radio is essentially a radio that is able to self-assess its demands and access available networks in a region on arrival, maintaining its privacy. It is a reasonable possibility that technology would eventually make this possible, which means regulation has to look ahead and be proactive rather than be reactive to inevitable landscape shifts brought upon by unforeseen events, as happened in 1912.

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