A Dynamic Policy License for Wireless Spectrum Management

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Thesis directed by Prof. Timothy X Brown

Electromagnetic spectrum for wireless communications is fully allocated by regulatory authorities, but this does not mean that it is fully utilized. Demand for greater capacity and new services requires new regulatory and technical models for spectrum sharing. This thesis develops a regulatory model denoted the dynamic policy license. The dynamic policy license combines the assurances to licensees that come from holding a fixed license while maintaining regulatory flexibility. A dynamic policy license is similar to a traditional spectrum license that specifies a bandwidth, power, center frequency, location, and other parameters. However, one or more of these parameters is subject to change by the regulator over time. The allowed changes are restricted by the license to provide assurances and predictability to the licensee. The opportunities and challenges that this presents to both regulators and licensees is described.

We examine, retrospectively, the application of the dynamic policy license to the case of Nextel Communications interfering with public safety communications. The resolution required several proposals by the FCC and others and over 2,200 filings by interested parties. Our license proposal is intended to provide flexibility and certainty to a variety of situations, including (1) changes in technology, demand, or use; (2) coexistence between multiple services, and; (3) efficient use of spectrum over time.

Spectrum issues such as allocation and allotment, assignment, service rules, and compliance and enforcement continue as contentious management issues. We suggest that existing fixed licensing models are sub-optimal, and in some cases are themselves the source of inflexibility and artificial scarcity. We contribute development of a license model that augments existing approaches across a wide range of governance models and assignment strategies.

Increasing pressure on spectrum resources has prompted new approaches to spectrum sharing and coexistence. A blockchain-based smart contract in conjunction with the dynamic policy license is one approach to managing radio operations and spectrum needs. Smart contracts enable spectrum policies to move beyond static documents to become autonomous, dynamic, self-enforcing, secure, transparent, and auditable code that runs on the blockchain.

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Contents

Chapter

Tables

Table

Figures

Figure

Chapter 1

Introduction

1.1 The Dynamic Policy License

In what ways could an alternative spectrum licensing model improve spectrum management? This thesis develops the idea of the *dynamic policy license* (DPL) as a step toward that goal. The DPL provides greater flexibility for the regulator while still providing assurances to the licensee. It is a means of reducing the friction of transactions, and thereby enables spectrum use to attain a higher social and economic utility. A better spectrum management tool should also be useful when applied manually to simple situations, and capable enough to automate a broad range of more advanced spectrum management functions.

Continuing growth in demand for wireless services and applications is placing increasing pressure on spectrum resources. Spectrum scarcity is further explored in Section 2.1.2 and is clearly an ongoing pressing issue. Many licensing models exist, such as those discussed in 2.1.1, but they still leave the regulator with few tools to address change once the license is issued. Current models also fail to provide clear assurances to the licensee that they will have the spectrum they need for their service. Spectrum management models could also benefit by incorporating new technologies. In Chapter 4 we combine the dynamic policy license with blockchain technology to demonstrate how shared spectrum could be managed for mobile applications across borders.

The National Broadband Plan and other Federal Communications Commission (FCC) reports call for spectrum reform to enable new methods of meeting the growing demand for wireless spectrum [1,2]. The President's Council of Advisors on Science and Technology (PCAST) also examined this problem in cooperation with the National Telecommunications and Information Administration (NTIA) with a focus on government-held spectrum [3].

There are two dimensions to the issue of meeting growing demand for spectrum. One is the problem of spectrum scarcity, as the number of suitable frequencies available for radio communications is limited [4]. The second dimension is the manual, static approach to managing spectrum, an approach discussed by Akyildiz [5], among others. In the US, laws governing general spectrum management are passed by Congress. The executive branch often further develops general policies. The FCC is guided by the policies to make specific technical rules and regulations under the law [6]. These functions are accomplished with considerable planning and direct regulatory action, making the process slow and the results static [7].

One approach to addressing this problem is dynamic spectrum access (DSA). Under DSA, the regulator grants access to a range of spectrum bands with limits on how the DSA user interacts with existing services (e.g., to prevent harmful interference). In essence, the regulator defines a license where one or more parameters such as the transmit frequency are not fixed. Instead, there is a set of allowed parameters and the **licensee** is free to choose its operational parameters from that set over time.

The introduction provides background on the problem and an overview of the ideas in the subsequent chapters. Following the introduction, the next chapter explains the DPL in greater detail and provides several thought experiments to demonstrate the value of the concept and how it can be applied to spectrum management. Comments from notable spectrum experts are incorporated throughout. From here, we consider the DPL in the context of the case of Nextel Communications interfering with public safety radios beginning in the late 1990s. We consider the underlying issues in the associated FCC proceedings, and relate the DPL to these issues. A central point of this chapter is that certain spectrum management issues re-occur, even if the circumstances change. From an economic perspective, the dynamic policy license is a mechanism to reduce friction in transactions, and enable spectrum to move to a higher use or output. Chapter four is forward-looking and examines how the DPL, in conjunction with blockchain technology, could be used to manage cross-border spectrum issues for the Internet of Things. The aim of this chapter is not only to look forward to a time when spectrum sharing will be more prevalent, but also to demonstrate a more advanced application of the dynamic policy license for a more complex spectrum management environment.

We propose the dynamic policy license, which defines a similar set of parameters except it is the *regulator* who chooses the operational parameters from the set over time. The allowed set of variable parameters and values is pre-defined in the license and cannot be arbitrarily changed by the regulator. The license specifies the nature of the allowed changes, such as how often the regulator is allowed to make a change, how much advance notice must be given, and other service assurances for the licensee. As an example, to provide assurances to a licensee that spectrum will be available when needed while maintaining flexibility for the regulator, a DPL could guarantee access to 10 MHz of spectrum for 10 years with the provision that, with six months notice, the regulator can change the license to be centered at any frequency between 600 and 700 MHz.

The dynamic policy license consists of two components; the license specification and the policy directives. The *license specification* is the framework for the license. It consists of the possible sets of parameters that the regulator can direct the licensee to use, the conditions under which the regulator can make changes, and other common licensing terms (e.g., whether the license can be transferred). The specific parameter set that should be used by a licensee is communicated via a *policy directive* from the regulator. An initial policy directive is given at the start of the license, and the regulator can issue subsequent policy directives over time to modify licensee operation and manage the use of the spectrum.

Using dynamic policy licenses to manage spectrum resources can address several issues for regulators. A central concern for regulators is that once a license is issued, it is difficult to make changes that become needed over time. The DPL addresses this concern. It enables the regulator to manage:

- changes in technology, demand, or usage;
- coexistence between two or more services; and
- efficient use of the spectrum over time.

The capabilities of a DPL are illustrated by the following scenarios:

- Change in demand: A future decrease in the size of an allocation, perhaps because anticipated future demand is less. For example, operation on Channel 50 is assigned initially, but because of anticipated future vacancies and reduction in the allocation, the regulator wishes to move the licensee to Channel 30 in the future to repack the licenses in fewer channels so that channel 50 and other channels can be reallocated.
- Change in usage: The FCC might initially allow a high power mobile cellular service to facilitate efficient coverage at service launch. However, in anticipation of increasing user density, the FCC could tell operators that in the future their DPL will be adjusted to lower maximum allowed power levels to encourage more cells and reduce health concerns.
- Coexistence: In a service that needs to operate near a radar without causing interference, the regulator can change the service area or power levels based upon operational data as it becomes available.
- Efficiency over time: "Repacking" of bands to account for licenses that come and go over time.

In this thesis, we examine the opportunities and challenges to dynamic policy licenses when applied to the problems of spectrum scarcity and spectrum management. The concept is first contrasted with existing work, including policy-based cognitive radios. The structure and contents of a dynamic policy license are then presented. Several thought experiments are presented to illustrate the value of the DPL. Finally, the role of the DPL in spectrum management is explored.

1.2 The Nextel Interference Proceedings as a Retrospective Application

Beginning in the mid-1990s, the Federal Communications Commission (FCC) begin to receive complaints from public safety agencies about interference in their radio communications. The operations of mobile cellular wireless carriers, particularly Nextel, were determined to be the cause.

The FCC had a regulatory duty to resolve the issue. Public safety agencies sought to return to unhampered operations. Nextel took responsibility for their contribution to the problem and desired to end the considerable uncertainty and impact to their business. Despite the motivations of all involved, it took until 2004 to reach agreement on a resolution. Implementation of the accord took over three years more. The resolution required several proposals by the FCC and others and over 2,200 filings by interested parties.

Taking a broader perspective, many of the issues in the Nextel case could be traced back to a band plan created by the FCC. Nextel took advantage of new technology and regulatory arbitrage to move spectrum to a higher economic utility, but this resulted in interference for public safety. Direct regulatory intervention was ultimately necessary to adjust previous decisions and permit spectrum consolidation that reduced harmful interference. The final resolution was based primarily on rebanding. Had licenses been issued under a dynamic policy license, flexibility to reband, and perhaps even trade in a secondary market, would have enabled a quicker and less contentious process with a similar result.

The duration and complexity of the proceedings indicate that a better process would be beneficial. The spectrum license reflects many essential duties of the regulator, and we argue that a different type of spectrum license would provide greater flexibility for the regulator while still giving assurances to the licensee.

According to the Federal Communications Commission (FCC), some specific tasks related to radio spectrum management include allocation, allotment, assignment, and service rules. For spectrum in use, the regulator performs duties in monitoring, compliance, and enforcement. Kennard [8], Nunno [9], and the FCC [10] review these practices further.

Broad goals of spectrum management include achieving socially desirable objectives via the regulation of spectrum, including efficient use of the spectrum resources; see, for example, Cave [11]. Management includes planning, coordinating, and regulating spectrum usage to prevent causing or enduring interference. Users are assigned spectrum in specific frequencies or bands for specific purposes. Licensees are required to use the spectrum in accordance with the rules defined by the regulator. The regulator performs monitoring, compliance, and, if necessary, enforcement activities to ensure conformance with the rules.

As spectrum usage intensifies, it is beneficial for the essential tasks of spectrum management to be accomplished quickly and efficiently. The current system is slow and inflexible, leading to excessive delays for new spectrum licensees, in addition to long and complicated proceedings when changing circumstances require the intervention of the regulator. The manual, static approach to managing spectrum, summarized by Akyildiz [5] among others, contributes to an artificial form of spectrum scarcity. As noted by Lehr, among others, existing fixed licensing models are sub-optimal, and in some cases are themselves the source of inflexibility and artificial scarcity [12].

In this thesis, we consider the application of a new type of spectrum license model to the case of Nextel interfering with public safety. The duration and complexity of the proceedings necessary to resolve the interference issues provide an illustrated example of how the existing system is often slow and inflexible.

We apply the idea of a dynamic policy license (DPL) that is designed to give more flexibility to the regulator while preserving certainty for spectrum licensees. We earlier proposed the concept of the dynamic policy license and provided examples of how the license might be effective [13]. We consider the specific and more complex issues raised during the Nextel interference proceedings and examine how the dynamic policy license, had it existed, may have been useful in resolving the situation more easily. We also explore abstract issues from the specifics of the proceedings that still exist today, and for which the dynamic policy license could prove useful.

We summarize the Nextel interference proceedings from a particular standpoint while also advancing an idea to resolve similar situations more effectively in the future. We also further expand on our earlier idea, an application of the dynamic policy license. By proposing a more flexible way to manage spectrum, we contribute to the larger discussion on finding ways to utilize spectrum more intensively. Growing numbers of spectrum users and applications increase the probability of conflicts and call for faster, more flexible methods of finding resolutions.

While the timeline of the case study is linear, the analysis is systems-based. We examined spectrum issues that still exist today from the perspective of a historical case. The goal of this work is not to analyze the events of Nextel case specifically so much as it is to examine broader spectrum issues. We suggest that a new type of license, had it existed, could have helped address the fundamental issues beneath the Nextel case. The underlying problems re-occur still, and a more flexible spectrum license would be beneficial both for regulators and licensees. While we know how the events of the Nextel case transpired and were resolved, in this work, we discuss ways that an alternative licensing idea might have contributed to addressing the problems more expeditiously.

1.3 Spectrum Management With Blockchain and the Dynamic Policy License

This chapter brings together several current trends in technology to demonstrate how shared spectrum for Internet of Things devices could be managed using a blockchain-based smart contract. The increasing focus on the expected benefits of the Internet of Things is one of the drivers for the work. Billions of IoT devices are expected to be in operation soon, most of which will connect wirelessly. These devices are likely to share sensors, platforms, networks, spectrum, processing, and data. Sharing is, therefore, another central theme of this chapter. Demand for radio spectrum is also increasing, even without the additional needs created by the Internet of Things. Work on spectrum reuse and sharing is an active area of research [14, 15].

We proposed the Dynamic Policy License as a means of managing spectrum more efficiently. One option for using this new spectrum license is to distribute operational parameters to policy-based radios via a database. This model is established already for sharing spectrum in television white space and the Citizens Broadband Radio Service at 3.5 GHz [16].

Another current technology trend involves interest in applications of the blockchain as a trusted database. Nascent blockchain platforms enable the creation of smart contracts—computer code that can take specific actions based on specific conditions. The blockchain is well suited to meeting many of the needs of IoT devices and facilitating sharing.

In this chapter, we create a specific use case that brings together the IoT and the blockchain to assist with sharing spectrum. An IoT device used for supply chain tracking powers on and announces its capabilities and requests desired operational parameters through a smart contract running on the blockchain. Allowed parameters are calculated by the smart contract using regulatory databases in the country where the IoT device is located and transmitted to the IoT device policy-based radio. The radio verifies that the source and parameters are valid, and begins operation according to the assigned parameters. The process repeats as the IoT device moves to new locations or as time elapses.

Broadly, we demonstrate a concept for the more efficient use of spectrum through spectrum management and sharing. More specifically, we create a model for mobile IoT devices to get parameters to operate in shared spectrum across different borders and regulatory regimes. Our approach is a smart contract running on the blockchain that takes inputs from the radio and the appropriate country regulatory database. The device is, therefore, able to operate under the control of a single master contract or policy that assists in negotiating the separate country/regulatory databases. We envision the master contract controlling other IoT network functions as well, such as business parameters, making the addition of spectrum management a natural extension.

We investigate building the system model and interactions. We develop the architecture and functions of a blockchain-based smart contract. The smart contract assists with assigning spectrum and operating parameters to an IoT device with a policy-based radio. To bring the concepts together, we provide some background on the IoT, the blockchain, smart contracts, spectrum sharing, policy-based radios, and spectrum databases. Moreover, we demonstrate how these elements can work together in support of an example application.

Thus, the approach of the thesis is to create the concept of the dynamic policy license as a means to enhance efficient spectrum use and management. Also, to show that it is applicable to common spectrum management challenges both past and future across a range of circumstances. The license is a method to reduce economic friction, or transaction costs, and serves to maximize spectrum utility while providing a means to assist in minimizing interference. The next chapter provides further details on the concept, operation, and value of the dynamic policy license.

Chapter 2

The Dynamic Policy License

2.1 Background

This section reviews essential ideas leading to the concept of a dynamic policy license, including spectrum rights, spectrum scarcity, spectrum management, and policy-based radios.

2.1.1 Spectrum Property Rights, Commons, and Licensing

In the early 1900s, there was no clear method of allocating spectrum usage rights, and the increasing popularity of radio broadcasting led to a period where many broadcasts interfered with each other. Congress passed the Radio Act of 1927 which established the Federal Radio Agency, what would later become the Federal Communications Commission, and gave them authority for managing spectrum. A more detailed history may be found in Hazlett [7]. As spectrum was deemed a scarce national resource, it had to be carefully managed by the government. Limitations were placed on the number of users that could operate in a given bandwidth to reduce harmful interference. From the enactment of those first regulations until now, the government has maintained a **command and control** policy that determines the amount of spectrum allocated to different applications or services. While the cost of sub-optimal allocation has not been closely analyzed, increasing demand for limited spectrum resources indicates that more flexible and efficient spectrum management approaches would be beneficial.

In 1959 Ronald Coase proposed the idea of spectrum property rights assigned via price or bidding, rather than via other licensing approaches such as merit [17]. He argued that however well intentioned, a central regulator could never be as well informed or efficient at allocating spectrum as the market. A significant component of his proposition was that spectrum usage rights, once awarded, were not to be restricted regarding how the spectrum could be used, or regarding freedom to sub-divide, lease, or resell spectrum that had been purchased. Additional spectrum could also be purchased for any purpose from other license holders. All spectrum would, therefore, move to the use with the highest value. Over time, in the United States and elsewhere, spectrum auctions have become common, particularly for cellular mobile spectrum. While closer to the model proposed by Coase, use of the spectrum is restricted to certain purposes, and payment of the auction price represents a lease for the use of the spectrum rather than outright ownership.

The success of Wi-Fi and Bluetooth in the unlicensed Industrial, Scientific, and Medical (ISM) bands has created interest in another model of spectrum usage, often called Spectrum Commons Theory or open spectrum access, see Noam [18]. Proponents of this model argue that all spectrum property rights should be abandoned, and spectrum should simply be available for use as a common good. License exempt spectrum is always utilized on a shared basis. Since no license is required, it can be used by anyone who has authorized equipment. Access to license exempt spectrum is allocated based upon availability, and the capabilities of the device, such as the tuning frequencies and the maximum permitted power levels for a specific radio. Bandwidth becomes a common resource managed strictly via sharing protocols, and spectrum is managed by its users or user-devices rather than regulated by a central authority. An argument in favor of this approach is that users can pursue flexible and innovative uses of spectrum. An argument against this regime says that it can lead to the so-called **tragedy of the commons**, where spectrum becomes overloaded and unusable due to multiple individual users pursuing their own interests without regard for the interests of other users.

In practice, even the current model for license exempt bands is not completely open-access or purely spectrum commons. This situation reduces the potential for a complete tragedy of the commons. Spectrum is still under the control of a central authority such as the government, and government regulators impose rules that equipment manufacturers and spectrum users must follow to reduce conflicts. For instance, radios must be manufactured and certified to comply with certain parameters set by the regulatory authority, such as maximum transmission power limits or spectral masks. For some systems there may be additional requirements for avoiding interference by either active or passive means. For instance, dynamic frequency selection is required of wireless local area network devices operating in the 5 GHz band.

An impure spectrum commons may, therefore, come with different levels of restriction for different applications. A market-based commons treats spectrum like a park that charges an entrance fee. Users are free to use common spectrum once the fee is paid, but fees are set to prevent overuse. New Zealand has proposed the idea of spectrum parks that allow access to a group of users in a common band of spectrum on a shared and self-managed basis, an idea explained in more detail by Goodwin [19]. The ideal is to promote innovation and flexibility along with efficient use of the spectrum while keeping the cost of compliance and administration low.

Werbach has proposed the idea of a **supercommons** [20]. He argues that regulation should not be about a property rights or a spectrum commons approach as both are just different configurations of usage rights, although both approaches can still be used as complements to his idea. Instead, he argues that regulation should be about interference management, and should focus on regulating the wireless equipment. His baseline approach is a universal communication privilege that permits anyone to transmit anywhere at any time. This approach requires an efficient mechanism for preventing interference and resolving disputes.

Spectrum expert Professor Doug Sicker notes that models that are not either unlicensed or traditionally licensed have not taken off yet [21], but the trend in future spectrum property rights is toward systems that create more flexibility for both the spectrum rights holder and the regulator. Factual exclusivity may be reduced, but functional exclusivity can be preserved where necessary. Certain services such as mobile wireless and broadcasting have traditionally required exclusive rights to use spectrum, but many other systems can share spectrum effectively. Licensing may, therefore, depend on the type of service using the spectrum, but even this is changing. Television broadcasting shares available **white space** frequencies with secondary users in some jurisdictions. This work is not intended to advocate for one regulatory approach over another, and in fact, no single approach is most appropriate for every circumstance. Similar to the position taken by Werbach when proposing the super-commons, we focus on efficient regulatory and technical mechanisms rather than regulatory ideology. We propose an approach that can take advantage of modern radio and network technology to reduce interference, efficiently manage spectrum and spectrum transactions, and resolve disputes. The goal is to permit flexible spectrum use while giving regulators and licensees the ability to specify the range of this flexibility precisely.

2.1.2 Spectrum Scarcity

While cellular mobile is not the only area experiencing increased wireless demand, it is among the fastest growing and best documented of the wireless applications. A 2010 Presidential Executive Memorandum called for 500 megahertz of spectrum to be reallocated to mobile and fixed broadband use [22]. The National Broadband Plan, also released in 2010, called on the FCC to make an additional 500 megahertz of spectrum available to wireless operators [1]. Both documents attempted to address the recent dramatic growth in demand for mobile spectrum, a fact also noted in a 2012 report by the President's Council of Advisors on Science and Technology (PCAST) [3]. Even with the additional allocations, this spectrum will be insufficient to meet future mobile demand, and limitations on available spectrum places constraints on existing mobile services and new applications and innovations on those platforms.

Cisco Systems predicts a 57% compound annual growth rate in mobile data traffic between 2014 and 2019 [23]. This is equivalent to almost 100 times growth in demand per decade. If overall mobile demand were to double every year, as suggested by 4G Americas [24], this results in an expansion of demand of approximately 1,000 times per decade. This growth places pressure on wireless capacity to keep up with demand. Recent growth has been due primarily to two trends, Internet usage moving from wired to mobile, and video delivery moving from broadcast to Internet streaming, facts also noted in the report by Cisco Systems [23]. In addition to mobile and video, cloud-based applications are increasingly common, and they require the exchange of large amounts of data between remote data centers and local users. Even if all usable spectrum were allocated to mobile, it would be difficult to meet projected growth according to a report by the 3rd Generation Partnership Project [25]. The Federal Communications Commission released data in a 2010 report that detailed an impending spectrum deficit, where it was projected that demand would exceed capacity in 2013, and continue to get worse thereafter [26].

New spectrum deployments can reduce congestion for a period of time according to Fitchard [27], but growing mobile demand will result in continually declining data rates, and spectrum deployments cannot match increasing demand according to a report by Open Signal [28]. New spectrum deployments are also expensive. The FCC AWS-3 auction received top bids of $44.9 billion for 65 MHz of spectrum, which exceeded by more than twice the high end of $22 billion projected by analysts [29]. This amount is nearly equal to the total raised in all prior FCC spectrum auctions combined according to FCC Commissioner Rosenworcel [30]. Global spectrum is fully allocated, even in bands other than mobile. It is therefore difficult to re-assign new frequencies to mobile uses, as this requires regulatory re-allocation and clearing of the other spectrum bands. Only a relatively narrow range of radio frequencies have propagation characteristics suitable for mobile applications, with implications such as continued scarcity discussed in a report by the cellular consortium 3GPP [25]. Even if all suitable frequencies were allocated to mobile, this would only permit about three years of growth in mobile data according to the National Broadband Plan [1]. This suggests that re-allocation alone will not be sufficient to meet demand and that efforts to share spectrum and improve utilization through new technologies and regulatory approaches will also be required.

Improvements in technology and techniques such as small cell deployments and Wi-Fi offloading have provided increased mobile capacity, but they are insufficient to keep up with demand. Small cells are expensive to deploy, and have inter-cell interference and handoff overhead, placing a practical limit on cell density. Several industry groups working on 5G have created target specifications for the 2020s, including [31–34]. Given that 4G LTE-A technology targets a spectral efficiency of 3 bps/Hz, the ITU [35] believes it will be challenging to meet the 5G goal of 45 bps/Hz by the early 2020s with any technology currently under development. Even if this goal can be met in the next 10 years, this is an efficiency increase of only 15 times, against a demand increase of potentially 1000 times.

The FCC reports a wide variation in spectrum utilization over time and space [36]. This can range from 15% to 85% according to Akyildiz [37]. While fully allocated, the current fixed system of assigning spectrum via manual and static approaches leads to what some, such as the economist William Lehr, have called an artificial spectrum scarcity [12]. The scarcity reflects inefficiency of the allocation system beyond limitations in availability of the underlying resource. Economist Thomas Hazlett says, similarly, that regulation is often responsible for inhibiting spectrum from moving efficiently to its highest use [38].

Detecting and resolving conflicts can also be a time consuming and expensive process which, like spectrum management, could benefit from a more automated and dynamic approach. In this work, we present an approach for dynamic access and management of spectrum using dynamic policy licenses. This approach has the advantage of making spectrum available to a wider variety of uses and radio systems while enabling coexistence with incumbent primary users. Professor and spectrum consultant Linda Doyle says the DPL is an interesting licensing scheme, coming at a time when dynamic approaches to spectrum management are welcome in general [39].

While we use the example of growth in mobile demand to demonstrate the need for more efficient spectrum access methods, the approach proposed here is applicable to many other frequency bands and radio systems. Professor Linda Doyle sees particular value for licensing spectrum that may ordinarily have infrequent use, such as by military systems. She also thinks it would be a valuable approach to carrier aggregation, where a licensee has a baseline amount of spectrum, but can aggregate extra bands for greater capacity when they are available [39]. Professor Doug Sicker states that he thinks there may be a good case for sharing spectrum with Department of Defense users in the 1 to 2.5 GHz area, and also opportunities for sharing of radar frequencies. He notes that a key concern in these cases is the regulatory entity managing the spectrum. Government users are more likely to consider alternative licensing if it is managed by the National Telecommunications and Information Administration (NTIA), but this may be difficult to coordinate with commercial users normally licensed by the FCC [21]. Professor John Chapin notes that joint NTIA/FCC regulation is already proposed for the Advanced Wireless Service (AWS) bands, specifically AWS-3, and that this could be a good application area for the DPL [40].

Professor Doyle states that the DPL concept may currently be more suited to the developed rather than the developing regions of the world due to the lower demand for spectrum in developing regions [39]. However, Ananda Raj Khanal, the Director of the Nepal Telecommunications Authority, expressed current interest in the dynamic policy license concept. He stated that they watch developing regulatory trends carefully, and that technical and regulatory mechanisms for spectrum sharing and re-use are clearly the direction for the future [41]. Fred Matos of the NTIA, who also trains international spectrum regulators, points out that mobile demand and Internet penetration in developing countries is growing faster than in developed countries. Developing countries also have less wired and optical fiber infrastructure, instead depending on wireless. Modern spectrum management regulations are important now to accommodate future demand and maximize the benefits of investment in infrastructure [42].

2.1.3 Current Spectrum Management Inflexibility

Current licensing models result in too little flexibility for the regulator, with undesirable consequences for all spectrum users. Most licenses define a set of allowed parameters in the license and then let the licensee choose the specific parameters they will use in operation. Even what we call a fixed license typically specifies a maximum transmit power and the licensee is free to choose any power less than this maximum amount. Under the command and control approach to licensing, regulators must assume that the licensee could be transmitting at the maximum allowed power.

The flexibility and range of parameters are what distinguish the different licenses. Radio broadcasting licenses can be very specific about all aspects of the transmitter, frequency, location, modulation, and antenna. Area licenses give more latitude in the number and location of transmitters. Many recent licenses give the operator flexibility on the types of service, modulation, and protocols. Dynamic spectrum access gives great flexibility for licensees to use the spectrum and decide what transmissions are appropriate.

This range of licensee, not regulator, flexibility is evident across a wide range of governance models, regardless of whether it is a licensed, unlicensed, lightly licensed, spectrum park per [19], spectrum common advocated by Noam [18] or the supercommons model by Werbach [20]. A degree of operational flexibility is also preserved regardless of how the license is assigned: beauty contest, first-come first-served, by auction, or through device certification. Licensee flexibility is also a component of the type of access scheme, be it primary, co-primary, or secondary access.

What we emphasize is that once the regulator grants the license, the power to choose how to use the flexibility in the license is granted to the licensee. The regulator retains few procedures to change the license beyond cumbersome harmful interference proceedings.

Because of the limited ability to change terms after a license is issued, regulators make extremely conservative decisions on spectrum usage, or they engage in protracted discussion and analysis to try to predict a good a priori solution to an inherently complex problem. When discussing the problem with spectrum expert Professor Jon Peha, he stated that there are at least two kinds of problems. One is that the regulator needs to make decisions based on predictive models. Because they have uncertainty, they are not always correct. Another problem is that there are other uncertainties that are not about errors in a predictive model, such as the arrival of a new technology or a new class of users [43]. For instance, preceded by six years of preparatory work, the Regional Radio Conference of 2006 undertook coordination for the transition from analog to digital television broadcasting in ITU Regions 1 and part of 3, which cover Europe, Africa, and parts of Asia [44]. The conference included over 1000 experts from over 100 countries meeting for 34 days, and required the services of the European Organization for Nuclear Research (CERN) supercomputer to run the complex simulations needed. The result was a document of over 2,000 pages which covered the bands 174 to 230 MHz and 470 to 862 MHz for television broadcasting. The transition to digital television broadcasting was simplified by the fact that it involved a net reduction in the total amount of spectrum required to support existing uses.

More typically, to make way for new uses of spectrum, existing bands must be cleared, which is itself a complicated and lengthy process, often taking ten years or more according to Professor Linda Doyle [39]. While usage of the television white spaces is not proceeding as quickly as expected, adding in the time necessary to clear the television bands could be said to have added years to the process. Because of the time and effort required, band plans change slowly. Once assigned, regulators must otherwise wait until the license runs out to resolve an undesirable situation. These challenges become more acute as the pace of technology change increases and as demand on spectrum grows. In short, the regulator is burdened with making spectrum commitments in a complex and dynamic environment.

2.1.4 Policy-Based Radios

Next, we turn to cognitive radios, because more flexible radios are one means to permit more flexible spectrum use. The ITU in its 2012 World Radiocommunication Conference [45], and in its Recommendation 76 [46], recommended that regulatory administrations actively participate in studies on the deployment and use of cognitive radio systems. Resolution ITU-R 58-1 [47] encourages study in the use of cognitive radio systems, with particular attention to enhancing coexistence and sharing among radio communication services.

Policy-based cognitive radios, or more simply policy-based radios, are radios whose operational parameters are determined by so-called policies that specify permitted and prohibited sets of operational parameters as detailed in, for instance, Fette [48]. At any given time the radio may hold one or more policies. The policy-based radio then reasons which permissive policies allow it to operate without impinging on any prohibitive policies.

Policies are often conceived as time-limited leases that have a defined duration [49]. Professor John Chapin states that different timescales enable capabilities in different contexts. For instance, if the FCC could make changes with six months notice, for many proposed changes, this still enables proceedings to happen. At the two week timescale, secondary market transactions are possible. So a possible use for the DPL is to bring liquidity to secondary markets, which Dr. Chapin says the FCC has been trying to do for a long time [40].

The radio hardware must be sufficiently flexible that it can operate over a range of parameters. Software defined radio expert John Chapin stated that as a rule of thumb, a retuning range within ten percent, and maybe fifteen percent, of the center frequency is achievable at no additional cost. Military radios can retune over an octave or more, but this adds on the order of $1,000 to the cost of each radio [40]. Professor Linda Doyle stated the requirements more generally from a spectrum licensing perspective: the dynamic portion of the band being licensed has to be narrow enough to be fungible [39].

Policies enable the regulator to set out allowed uses of the spectrum for regulator-specified periods of time and provides an orderly mechanism to implement changes. What they lack are any explicit guarantees to the licensee that spectrum will be available once the time-limited lease expires, limits to what parameters the next time-limited lease may hold, and the number and frequency of future time-limited leases that must be accommodated by the licensee. For instance, while a permissive policy may give assurances that a radio can operate over a period of time, a new prohibitive policy can be issued at any time stopping operation. The dynamic policy license (DPL) addresses these issues.

Several machine-readable policy languages for communicating with cognitive radios have already been proposed. These include the OWL 2 Web Ontology Language in [50], SWRL, a semantic web rule language combining OWL and RuleML in [51], and the Cognitive Policy Radio Language (CoRaL) [52]. Agile radio and cognitive radio technologies can automatically process policies as explained by Mitola [53]. Such technologies enable the ability to efficiently make frequent parameter changes. Policies can also be created as natural language constructs which are then translated into machine-readable policies. Perich [54] has proposed a graphical user interface-based policy visualization tool. Certain computer languages, such as the Extensible Markup Language (XML), could be adapted to permit licenses which are both human and machine-readable. Policies are useful for providing precise and unambiguous parameter setting for all types of radios, policy-based or not, even ones where parameter changes require manual intervention.

A dynamic policy license can be implemented within a policy-based radio framework. What is emphasized in the DPL is that the range of allowed parameters in policies are predefined at the time the license is issued, the frequency and conditions for operational change imposed by policies is predefined, and the existence of a policy that enables the radio to operate is guaranteed. Table 2.1 characterizes the dynamic policy license relative to other types of licenses.

Table 2.1: License Characteristics

Assignment	Access Guarantee	No Access Guarantee
Fixed	Fixed License	Secondary Access
Dynamic	Dynamic Policy License	Dynamic Spectrum Access

2.2 Elements of the Dynamic Policy License

The dynamic policy license consists of two components, the *policy directives* and the *license specification.*

2.2.1 Policy Directives

Policy directives define a set of operational parameters that may be used by a radio at a given time. The policy directive is envisioned to be implemented through spectrum policies, a concept which is already well established in dynamic spectrum access [55]. Spectrum policies specify parameters such as the spectrum band, the power levels, the antennas, the geographic areas, and the time that the directive is valid. Parameters may be fixed by the regulator, or be variable to provide some flexibility to the licensee. For instance, the policy may describe a specific TV transmitter including transmitter location, transmitter height, antenna type and orientation, channel, and power level. A more flexible policy may define a geographic area, a frequency range, and a maximum effective isotropic radiated power (EIRP); and the licensee is free to choose the service it offers within these limits. Each policy directive references the license that they are modifying and we rely on secure distribution techniques developed for spectrum policies to ensure that the policy directives are being issued by authorized sources. An example of secure distribution techniques for policy-based radios is given by Brown and Sicker [56].

A licensee receives such policy directives over time as part of the regulator's spectrum management. When the regulator wants the licensee to transition from one set of parameters to another, it can choose several strategies. A soft transition would give the licensee two or more valid policies over a transition period so that the licensee can phase into the new policy directive and out of the old policy directive over time. A hard transition would have only one policy directive valid at any time. A new policy directive would take effect only after the old policy was no longer valid. An old policy directive becomes invalid either because it has a time limit that expires or because the regulator sends a revocation of the policy directive. Revocations specify the policy that is being revoked and the time when the revocation takes effect. Note that the regulator can advertise transitions to licensees with advanced notice. New policies and policy revocations can be sent long before they come into effect, allowing time for resource and engineering planning. The amount of advance notice given is part of the license specification.

A fully specified description of operational parameters can be long and difficult to distribute, especially when the changes are frequent or the policy distribution channel has limited bandwidth. As an optimization to facilitate distributing directives, the policies can be in the form of **delta policies** where only parameters specified in the delta policy are changed, and the other parameters remain unchanged.

2.2.2 License Specification

The license specification sets out the terms of the license:

- A description of all policy directives that are allowed to be assigned during the license.
- The conditions for any allowed changes from one parameter set to another.
- Regulatory parameters such as the parties involved, the ability to sublease, and whether it is primary, co-primary, or secondary access.
- Business parameters, such as fees and payment.

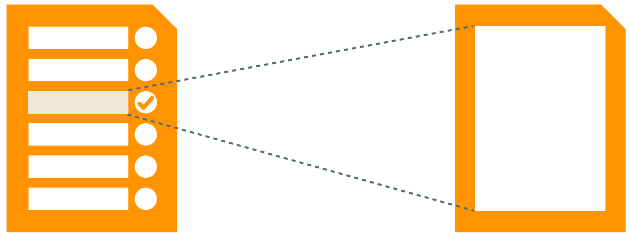

Figure 2.1: The full *license specification* (left) and specific *policy directives* (right).

2.2.2.1 The set of all policy directives

A central feature to the dynamic policy license is that the regulator cannot arbitrarily define operational parameters for the licensee. However, instead, they come from a restricted set. The range of parameters is defined in the license. The restrictions can come in two forms. In the first form, certain parameters are defined in the license and cannot be changed by subsequent policies. For example, the type of service (e.g., mobile broadband) and area of operation may be fixed by the license. Through delta policies, these parameters do not ever need to be sent in the policy directives.

The second type are **policy directive templates**. The template is fully specified if it includes specific values for all necessary details. In principle, the license could simply enumerate all possible policy directives and include one fully specified template for each possible policy directive. However, there may be too many combinations to enumerate, or some parameters may have a continuous range that cannot be enumerated. In this case, the policy directive templates can have parameters that specify the set of possible values. These can be either discrete or continuous sets, e.g. $[700, 710, 720, 740]$ MHz vs. $[700 - 740]$ MHz.

Unless a license fully specifies all parameters, the licensee cannot operate until they receive the first policy directive from the regulator. This directive may be issued with the license or at some later time if the regulator wishes to issue the license now but defer setting the licensee parameters until later.

As a special case, we can define an ordinary fixed license. To do this, the license specification can define all the parameters in the license and have an empty policy directive template. Alternatively, the license specification can give a single fully specified policy directive template and specify that there can be no further policy directives.

2.2.2.2 Defining allowed changes

The licensee will want to know how often the license can be changed by the regulator via policy directives and under what conditions. To specify how often the license can be changed there are three types of restrictions. The first is an absolute number limit. For instance, after the initial directive, the license may only be changed once. A second is a limit on the minimum time between each change. For instance, a policy directive must be valid for at least one year before the next directive comes into effect. A third is a limit on when they can occur. For instance, policy directives may only come into effect after January 1, 2020. Alternatively, at a finer grain, policy initiatives may only come into effect between midnight and 2 am.

While it may be possible to specify some of these restrictions in the policy directive template, not all can be specified this way, and some specifications can be overridden by a policy directive revocation. Therefore it is best to be explicit about the temporal change restrictions.

In addition to the temporal restrictions, there may be conditions that must be met on each change. One condition is advance notice. This specifies how much time before a policy directive comes into effect the directive needs to be communicated to the licensee, e.g., one-month advance notice. A second condition is transition policy. For instance, how much of a transition period, if any, is given to the licensee when they transition from one policy directive to the next?

There also can be conditions on quality of service, such as a minimum bandwidth or coverage that is afforded to the licensee. Many, but not all, of these can be written directly into the policy templates, and it is useful to be explicit. One quality of service measure is availability. This may simply be 100% of the time, or there may be some specification on the maximum duration of gaps between when one policy directive expires and the next comes into effect. There may also be a guaranteed available time in a given period (e.g., 99.9% of the time in any given year).

Other conditions may be written into the dynamic policy license but depend on non-quantifiable factors. For instance, a policy directive may only be issued once the digital television transition is complete. Alternatively, a policy directive may only be issued if microwave landing systems are being deployed. Or, a policy directive may only be used to resolve harmful interference with a nearby radar system. As can be seen, many of these go beyond machine-readable policies and require human intervention to validate.

We base the dynamic policy license concept on machine-readable policies and advocate them as a mechanism for automating the management of the dynamic policy license. However, machine-readable policies do not cover all aspects of the dynamic policy license, nor are they necessary for a DPL implementation. A DPL, in principle, can be managed completely through directives written in a human-readable form on paper sent through ordinary postal mail. Professor Linda Doyle states that having a high and low-technology application of the DPL is important for getting buy-in. It is also a way to shift to a more dynamic way of thinking about spectrum while still being impactful [39].

2.2.2.3 Regulatory parameters

The dynamic policy license may contain special regulatory parameters. For instance, a dynamic policy license may be written for operation in spectrum that is subleased from a primary user, but the subleasee might be prohibited from further subleasing the spectrum. The primary user might be prohibited from further subdividing the spectrum granted to it, or use could be granted for certain types of systems or operations, but not for others. The regulator may specify an intermediary such as a policy manager or spectrum broker who holds the license and issues policy directives in lieu of the regulator.

2.2.2.4 Business parameters

A dynamic policy license, particularly one involving a spectrum broker or a sublease, could contain the business and payment terms as well as regulatory and operational parameters. Operation of a secondary user system could be subject to payment verification by the primary spectrum holder, for instance.

2.2.3 Dynamic Policy License Distribution

The dynamic policy license requires communication of the original license specification and communication of the policy directives over time. Except in highly dynamic scenarios that are issuing and reissuing licenses frequently, ordinary license communication can be used by the regulator to communicate the license specification to the licensee.

For the policy directives, many simple push mechanisms are possible, such as an email to the contact of record for the licensee. However, the regulator will want confirmations that the policy directives have been received by the licensee and some licensee confirmation protocol will be required. Instead, the regulator may opt for a pull model where the directives are made available in a database, and the onus is on the licensee to check the database for new policy directives. The regulator may make the period of validity for a license directive intentionally short so that the licensee must check into the database frequently to maintain continuity of the license.

Different database architectures can be used (distributed or centralized, regulator-managed or delegated, etc.). Note that herein we are only discussing the distribution of policy directives between the regulator and the licensee. The distribution of the policy directives to the actual radio systems is application specific and outside the scope of this work.

Table 2.2: The License Specification Sets Out the Terms of the License

Terms	Description
The set of all policy directives	• Certain parameters are defined in the license and cannot be changed by subsequent policies. • Policy directive templates. • Unless a license fully specifies all parameters, the licensee cannot operate until they receive the first policy directive from the regulator.

Defining allowed changes	• An absolute number limit.
	• A limit on the minimum time between each change.
	• A limit on when they can occur.
	• Some specifications can be overridden by a policy directive revocation.
	• In addition to the temporal restrictions, there may be other conditions:
	  ○ Advance notice,
	  ○ Transition policy,
	  ○ Minimum bandwidth or coverage that is afforded to the licensee,
	  ○ The maximum duration of gaps between when one policy directive expires and the next comes into effect.

Regulatory parameters	The parameters such as: • The parties involved, • The ability to sublease, • Whether it is primary, co-primary, or secondary access.
Business parameters	• Business and payment terms, • Whether subleasing of the licensed spectrum is permitted.

2.3 The Value of the Dynamic Policy License

This section introduces four thought experiments that demonstrate the value of maintaining flexibility in channel assignments and discusses the idea of the value of the DPL as an economic option on future flexibility. It also begins to detail elements of a conceptual framework for dynamic policy licenses, including some requirements and benefits.

2.3.1 The Value of New Assignment Models

In this thought experiment, consider a protracted band repacking process. The process will yield new channels to be auctioned off, but the precise channels depend on the process outcome. The regulator could wait until after all the channels are available and determined and then hold the auction. However, this will lead to idle spectrum during the auction and during the subsequent time necessary for auction winners to engineer a radio system, acquire equipment, deploy a service, and acquire initial users. The spectrum could be idle for a long time. Further, this process favors large incumbent operators who have better resources to pay for the licenses and then reach initial service launch faster than smaller startups.

Alternatively, the regulator could auction off these to-be-determined channels ahead of time so that the new licensees are identified and have engineered their system, acquired and deployed equipment and have initial users ready to use the new channels as soon as they become available minimizing the time the spectrum is idle. This enables new uses of spectrum to be available sooner, increasing its societal value.

This thought experiment is independent of the dynamic policy license. The role of the dynamic policy license is to clearly specify what is known about the license ahead of time and to specify within the DPL framework the possible channel assignments and other conditions to minimize the residual risk to the potential auction bidders. The policy directive with the channel assignment could specify the date when the previous licensee is required to turn off their transmitter months in advance allowing the new licensee to prepare and use the spectrum as soon as possible. By minimizing risk and providing early well-planned access to spectrum, the DPL can help to maximize the value of the licenses to all potential bidders.

2.3.2 The Value of Planned Changes

An experiment using game theory demonstrates the value of planned transitions. Let there be a service A that needs spectrum to operate. There exists a band that has been allocated for a valuable future service (e.g., microwave landing systems), denoted service B. Although service B is anticipated to be valuable, other technologies may obviate the need for service B and the spectrum may or may not be needed in the future. Meanwhile, there is a service Z that is using spectrum now but will free up spectrum in the near future.

The regulator has two choices. One is to wait until service Z has freed up spectrum and then allocate it to A. In this case, the value of service A is realized only in the future and not now. Alternatively, service A can be allocated to the spectrum of service B now. If service B is never realized then there is no cost to allocating now and the value of service A is realized now and in the future.

The question is what happens if service A is allocated now and service B is realized? In this case, we have two choices. The first is that service A is **fixed** and service B cannot be offered in this spectrum. The second is that service A **moves** and suffers a cost to move to the service Z spectrum.

To make this concrete, consider time divided into two periods, now and future. Consider the value of service A in each period to be 1 and the value of service B, if it is realized and allocated in the future, to be 3. Let the cost for reallocating service A to new spectrum be denoted c. The possibilities are shown in Fig. 2.2.

In the scenario where allocating service A is fixed, if the regulator allocates now, the value is 2 for the two periods of service A no matter what happens. If they wait and see, they earn 1 over the future period for service A no matter what happens and if service B is realized they earn an additional 3. In this case, if the likelihood that the new service is

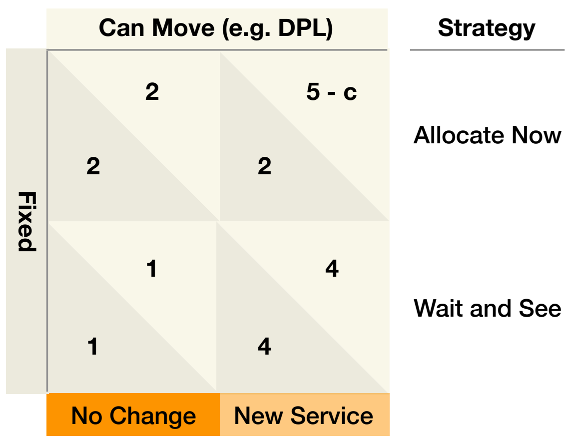

Figure 2.2: Game theoretic diagram showing the value of different spectrum allocation strategies and future outcomes. The dark lower-left numbers represent the value of the fixed strategy over the two periods in each scenario and the light upper-right numbers represent the value over the two periods of the strategy that can move in each scenario.

realized is not low, the regulator will be inclined to wait and see rather than allocate now. In addition, the fixed license requires the regulator to make a "bet" on whether the new service will or will not be realized and requires further resources (e.g., proceedings) to decide the likelihood of there being no change or the new service being realized.

In the scenario where allocation for service A can change, the outcome changes if the regulator allocates service A now and service B is realized in the future. In this case, the value is $5 - c$. So, as long as the cost to reallocate, c, is less than the value of offering service A now, the allocate now strategy dominates the wait and see strategy. Further, the value of this strategy dominates any strategy of giving service A a fixed license and it does not require the regulator to bet on the likelihood of any change. It does require an estimate of the cost of the change but this is a potentially simpler engineering calculation.

The role of the DPL is to provide assurances to the provider of service A that the new spectrum will be available so that they will invest in service A (maximizing the value of service A now), and to provide a clear plan of how any change might take place so they can factor that in an orderly way into their investments and help to minimize the cost, c. Without the DPL, changes would use ad hoc and expensive proceedings that could dramatically increase c and reduce investment in service A during the uncertainty of the process. In other words, DPL provides a method for the regulator to manage the spectrum to maximize its value.

2.3.3 The Value of Flexibility

An experiment can be constructed to demonstrate the value of flexibility in dynamic policy licensing. Suppose the regulator licenses a new service. For instance, it might set aside a few FM broadcast channels for temporary low-power FM broadcasts. Over time licensees establish transmitters over some large area. Licensees are assigned one channel from some set of N channels. The concern is that if two licensees are within distance R of each other and are assigned the same channel, then there will be interference and conflict for the channel.

As a new service, it is difficult to predict future requirements, and the regulator does not have enough information or resources to do a full analysis of how to assign channels to avoid interference. Further, since new licensees appear over time, it is hard to make a systematic analysis of what assignments can be made now that account for all possible future new licensees. Therefore, to simplify spectrum assignment and management, the regulator uses the following random assignment scheme.

The regulator divides the N channels into $\frac{N}{2}$ groups of adjacent channels: The first group is Channels 1 and 2; the second group is Channels 3 and 4; and so on. Each new licensee is randomly assigned to one of the $\frac{N}{2}$ groups. The regulator then analyzes the two channels in the group to see if it is possible to assign the potential licensee to one of the two channels without conflict. If it can, the new assignment becomes a fixed assignment, and a license is issued. Otherwise, no channel is assigned, and no license is issued.

Alternatively, the regulator again divides the N channels into $\frac{N}{2}$ groups of adjacent channels. However, the regulator tells licensees their license requires them to accept some future regulatory flexibility. They may need to change back and forth between the two adjacent channels in the future as directed by the regulator. For licensees, the cost of equipment such as amplifiers, antennas, receiver filters, etc. that work in two adjacent channels may be modest if they can plan and invest up front.

To model the FM licensees that arrive over time we add licensees one at a time at random locations. Now suppose we reach a point where a new licensee is assigned the same group as an existing licensee within distance R. In both the fixed and flexible scheme the regulator can assign the channel in the group that is not being used by the existing licensee.

We continue adding licensees in this way, and we may reach a point where a new licensee is assigned the same group as two existing licensees within R. If the three licensees are all within R of each other, then there is no way to assign two channels without conflict, and the license is denied. However, for some geometries, the two existing licensees are not within R of each other. We have two cases. If the two existing licenses are assigned the same

Table 2.3: License Density Increase Afforded by Regulatory Flexibility

Probability Get License	Density Increase
0.9	14%
0.99	16%
0.999	16%
0.9999	16%

channel within the group then in both fixed and flexible schemes the regulator can assign the channel in the group that is not being used by the existing licensee.

However, if the existing licensees are assigned different channels and exhaust the possible channels in the group, the fixed scheme fails and the license is denied. In the flexible scheme we can change the frequency of one or the other of the existing licensees to the other channel in the group to resolve the conflict and the license is assigned.[1] This allows the regulator to pack in licensees more densely for a given probability of no conflict and the license is issued. How much more densely? In Appendix A we analyze both scenarios and determine the density increase afforded by flexibility as a function of the probability of getting a license. The results are shown in Table 2.3, where license flexibility supports 14% to 16% more licenses depending on how stringent is the probability of getting a license.

2.3.4 The Value of Adaptation

A fourth thought experiment explores the value of adaptation. Consider coexistence between a hypothetical radar system and a fixed broadband service [57]. In the case of a fixed license, the regulator may set very conservative parameters such as a large exclusion zone around each radar installation to protect the radar. As a result, many valuable coverage areas for the broadband service may be excluded.

With the dynamic policy license, the regulator can start with these same large exclusion zones and then issue policy directives to grant access to areas within the exclusion zone at

[1] This frequency change may propagate to neighbors of this neighbor and so on.

different power levels for short time periods. In these periods, the operator can set up temporary transmitters. If the radar experiences harmful interference, the regulator can issue immediate revocations of the policy directives. However, if no interference is observed, policy directives for longer periods can be issued. It is expected that over time a power level that can be used without causing harmful interference will be determined in most areas. The licensee can trade off more lower-power base stations versus fewer higher power base stations as a result of this process. The dynamic policy license enables a framework for specifying how this adaptation procedure will proceed and the conditions for testing and revoking the licenses. The incumbent is given assurances that their service will not suffer any long-term harmful interference while the dynamic policy license grants specific rights to the licensee so that they can appropriately value the license.

These four thought experiments demonstrate the value that the dynamic policy license can bring. First, it encourages more efficient use of the spectrum. Regulators are more likely to put spectrum to use sooner, and it provides them mechanisms to bridge different spectrum over time while providing service guarantees that encourage investment by licensees. It also enables more dynamic short term assignments that can be managed over time without protracted procedures that try to anticipate future changes. Finally, it provides a mechanism to put more spectrum to use in more places while providing protections to incumbent licensees.

2.3.5 Regulatory Flexibility as an Economic Option

From an economic perspective, the dynamic policy license is an option for future flexibility purchased by the regulator. Given the choice of a traditional fixed license and a license that may require a larger initial equipment investment or future expense to accommodate flexibility, the fixed license would be preferred by the licensee. As a result, the licensee's willingness to pay is lower for the spectrum awarded under a DPL. Professor Doug Sicker states that the amount of revenue a license model can generate is one of the "goodness tests" of spectrum analysis. In the past, non-traditional license models have resulted in much lower revenues at auction, but this could change with more adaptive equipment and business models [21]. The DPL 'option price' is the difference between the revenue the regulator could have received from the traditional license and the revenue paid by the licensee. In the case of an entity purchasing a DPL through bidding, the DPL option price is paid by the regulator through lowered revenue. In other cases (e.g., government users), the DPL option price is paid by the licensee through higher costs which reduce other investment in the service. In the worst case, the DPL option price is high enough to deter any user of the spectrum.

A project's value can be characterized through an investment analysis of the expected *net present value* (NPV) of all revenues and costs over the life of the project. Bidders for a license, for example, would be expected to be prepared to pay up to the project value, less an internally-determined rate of return on their investment. Additional costs for the DPL could be in the form of more expensive radio equipment with the capability to operate over a wider frequency range or the outright replacement of a radio that can operate at a different center frequency at some point in the future. Alternatively, there may be business and marketing expenses incurred to move customers to the new frequency. After estimating these additional costs, the NPV can be computed taking into account the likelihood and timing of a change request. In this framework, the DPL option price, P_{dpl}, is the NPV of the costs under a DPL license, C_{dpl}, less a similar NPV cost analysis for a fixed license, C_{fl}:

$$P_{\text{dpl}} = C_{\text{dpl}} - C_{\text{fl}}.$$

In the case of an auction scheme to assign spectrum, P_{dpl} represents the **option price** reflected in lower bids to the regulatory agency.

The example is a narrow view of a DPL versus a fixed license and should reflect two additional considerations. One is that through a DPL the licensee may gain access to spectrum that would otherwise have been unavailable, or may gain access to that spectrum sooner. Alternatively, the spectrum allocated through DPLs may be better managed and more valuable to licensees compared to fixed licenses. For example, DPLs may resolve harmful interference more efficiently. Similar to above, we need to also consider the NPV of DPL benefits, B, to compute the value, V, of a DPL:

$$V_{\text{dpl}} = B_{\text{dpl}} - B_{\text{fl}}.$$

In some cases, V_{dpl} may even more than offset P_{dpl}. In these cases, licensees may, in fact, prefer the DPL over a license with traditional provisions.

The other consideration is that auction prices do not always fully capture all utility in a transaction. It is a duty of the regulator to maximize the socio-economic utility of spectrum. A DPL may enable new services to be offered or brought to market sooner, and may increase consumer satisfaction. These benefits are exogenous to licensees and the auction system, and their value is not captured in the project value or the price bidders are willing to pay for a license. However, a regulator may make a societal cost-benefit analysis when choosing whether or not to design and use a DPL. Professor Linda Doyle notes that while the DPL may have lower auction value, it may also cost less by, for instance, easing the process of clearing bands [39].

2.4 Spectrum Management via the Dynamic Policy License

Broad goals of spectrum management include achieving socially desirable objectives via the regulation of spectrum, including efficient use of the spectrum resources [11]. This work includes planning, coordinating, and regulating spectrum usage to prevent causing or enduring interference. According to the FCC, some specific tasks related to spectrum management include allocation, allotment, assignment, service rules, and finally, monitoring, compliance and enforcement [8–10].

Some advantages of using dynamic policy licenses for spectrum management are shown in Table 2.4. From the regulator's perspective, the dynamic policy license adds clear benefits. To the extent that it leads to greater and more efficient use of the spectrum while protecting incumbent licensee services, it benefits future and present licensees as well.

Table 2.4: Advantages of Using Dynamic Policy Licenses For Spectrum Management

Advantage	Description
Allocation and Allotment	A license system with the capability to adapt to other spectrum uses and the ability to periodically assign different frequencies provides more flexibility in allocation and operation for the regulator and radio system operator. Allocation transitions can be factored into licenses with a well-defined mechanism for effecting the transition that allows for future uncertainty. Allotment transitions can also be factored into the license and licensee planning.
Assignment	Spectrum assignment can be made dynamic. A dynamic policy licensee can have their spectrum access rights assigned, changed, or managed using a quick and efficient mechanism. This encourages regulators and incumbent spectrum holders to be more flexible in sub-leasing spectrum, and encourages innovation in secondary uses. The incumbent may have more trust in regulator-managed dynamic policy licenses than in more open-ended dynamic spectrum access schemes. Risk is limited because any potential interference or other problems can be addressed via an updated directive, which reduces concerns for all license stakeholders.
Service Rules	Dynamic policy licenses can be encoded in a machine-readable form. This provides more options for accommodating future changes or necessary upgrades. An appropriate radio does not need to be replaced or go through another certification process based upon a change in rules or capabilities.
Monitoring, Compliance, and Enforcement	Spectrum sharing increases the likelihood of interference and other conflicts. Automating compliance is likely to be a required component of automating sharing, and a license framework that allows this will make the compliance process easier and less expensive. Dynamic policy licenses provide additional methods for determining which radio may be causing interference or is otherwise misbehaving. Once the problem device is identified, a directive from the regulator can change operating parameters of the licensee using the terms of the dynamic policy license.

Other benefits of more intensive spectrum use include increasing unit sales for equipment manufacturers, and allowing the use of new radio technologies that can be incorporated more easily into spectrum allocations, encouraging equipment innovation. The dynamic policy license itself will encourage the use of agile and policy-based radio technology.

The dynamic policy license will encourage new business models. Regulators may delegate management of some dynamic policy licenses to spectrum brokers or other intermediaries. License owners can use the dynamic spectrum policy framework for managing users in their spectrum by being able to clearly define the parameters of operation and service level agreements. The service of delivering policy directives to licensees can also be a new business. Since much of the spectrum license can be encoded into machine-readable form, it will also encourage more and better automated analysis of spectrum usage over time. Professor Doug Sicker states that in addition to flexible equipment, there is potential for more flexible business models. For instance, by leasing infrastructure from, say, Crown Castle or American Tower, a wireless provider may have sufficient flexibility to adapt to changes at a reasonable cost [21]. Professor John Chapin foresees business models where the user accepts some counterparty risk. For instance, the user may be offered a lower price if they are willing to take the chance that their data rate may drop for a period of time. The risk could be offset if it is possible for the service provider or the user to purchase additional bandwidth from another operator, if necessary. In this way they could predict the cost, but treat it as a risk cost that doesn't have to be paid immediately. He also notes that for some uses, such as lower data rate systems, including something like a GSM or LTE modem as a backup would allow mobile carriers to move data if needed, and the incremental cost of the modem and data plan can be quite low [40].

In these cases, though we used the term "regulator" throughout this thesis as the source of the dynamic policy license, it should be understood that the source of the license is the spectrum broker, license owner, or other entity. Professor Jon Peha notes that any entity using any part of the system, or even adjacent channel users, could be stakeholders to a license. In some cases, we do not yet have a good idea of who those future stakeholders might be. He states that there could be many models for providing services, with different roles for government versus service providers. He says that we are only beginning to explore what works [43].

Against these many and varied benefits, we must weigh the cost of the dynamic policy license. These licenses are inherently more complex. Each policy directive must be checked for compliance against the original license specification to be sure it meets the parameter restrictions, temporal requirements, and other conditions. Mistakes can be made, and procedures need to be in place to resolve these mistakes before they lead to conflicts in spectrum usage or unwanted interference. Security procedures must be in place so that false directives cannot be created or valid ones manipulated, concepts discussed by [58]. These procedures should enable licensees to verify the integrity and provenance of the policy directives they are using.

Due to the possibility of future modifications, a DPL may require greater engagement by the regulator during the lifetime of the license. This may still be preferable to a situation where the regulator wishes to make changes to a fixed license but finds it difficult to do so, or perpetuates what it knows to be a sub-optimal allocation of spectrum. To the extent that the DPL permits more regulatory flexibility it may, in fact, reduce the burden on the regulator (e.g., in the case where it may be easier to resolve an interference conflict). For certain tasks, such as the distribution of policy directives to policy-based radios, the regulator is free to choose their level of engagement. For example, both the US and the UK have enacted regulations permitting radio operation in television white spaces, see the FCC [26, 59, 60] and Ofcom [61]. White space primary radio devices are controlled by geolocation database engines. In the US the regulator has certified selected third parties to operate the geolocation database engines, with very little involvement by the regulator after certification. The UK regulator Ofcom has taken a similar approach, but unlike in the US, the regulator actively participates in the calculation of certain radio operation parameters which propagate to the third-party databases. The regulator could make similar choices for services subject to a DPL, particularly since this type of license more easily enables the involvement of a third-party spectrum manager.

A dynamic policy license may be inherently less valuable to an operator than a fixed license, and therefore the licensee may reduce investment in deploying a service subject to future changes and uncertainties. A poorly designed license may yield little or no revenue in spectrum auctions or may have reluctant and slow uptake among licensees. For example, the 2008 D Block spectrum auction failed to receive a single bid [62]. It is incumbent upon the regulator to design the dynamic policy license with these concerns in mind. For instance, while being able to reassign a licensee to any channel at any time provides the most regulatory flexibility, for a high-power broadcast service each additional channel that is used involves investment in specialized frequency-specific high-power amplifiers, filters, and antennas; and each change requires manual intervention of skilled technicians. As pointed out by spectrum regulatory expert Dale Hatfield, these conditions are not necessarily prohibitive to a DPL, but they will impact the value of the spectrum and of the license [63]. As seen in the flexibility example in Section 2.3.3, restricting the channel flexibility to two adjacent channels was still enough to provide substantial benefits.

Regulators need to work with potential licensees so that both parties understand the trade offs and benefits of different choices in the design of the dynamic policy license. As seen in the planned changes example in Sections 2.3.1 and 2.3.2, potential licensees should understand that the dynamic policy license is a path to getting access to spectrum sooner. As seen in the adaptation example in Section 2.3.4, quite onerous rules in the short term may be necessary to provide any access to spectrum at all. In other cases, there is a specific change in spectrum usage driven by changes in demand and technology, and the dynamic policy license can be viewed by the licensees as providing them explicit rights and protections during a transition that would otherwise be implicit or simply not present. In this way, the dynamic policy license can **reduce** risk and uncertainty.

For many services, the flexible and agile technology required of dynamic policy licenses already exists and is part of the service for other reasons. Mobile phones already work across many bands and even switch between mobile phone and Wi-Fi services as needed to maintain connectivity. Radio technology will continue to evolve, and the ability to incorporate more flexibility in radios will increase. These trends, as well as continued spectrum demand, will drive interest in new models of spectrum access such as dynamic policy licenses. A new type of license, especially if assisted by new technologies such as geolocation databases, enable more flexible and efficient spectrum utilization and managment.

Chapter 3

A New Spectrum License For Old Circumstances: A Retrospective Look at the Nextel Interference Proceedings

The previous chapter demonstrated the flexibility and value of the dynamic policy license through several thought experiments. In this chapter, we utilize a well-known case from the 1990s of Nextel Communications interfering with public safety radios to further expand on fundamental spectrum management issues.

Several of the ideas in this chapter grew from a conversation with economist Thomas Hazlett at the TPRC45 conference [38]. Hazlett had himself recently written about the Nextel case [64]. While he focused more on the definition of property rights, in doing so, he noted the influence of transaction costs, or economic friction, on efficient spectrum management. Also central to this chapter is an idea from Coase [17]: "It is sometimes implied that the aim of regulation in the radio industry should be to minimize interference. But that would be wrong. The aim should be to maximize output."

As will be shown, many issues in the Nextel case were related to an early band plan created by the FCC. New technology enabled new uses of this spectrum. The market moved specific bands of the spectrum to a higher economic output, but in so doing, created interference for adjacent band users. Regulation contributed to the untenable situation and also prevented the market from resolving it without direct regulatory intervention. Regulation may have been said to play a role in artificial spectrum scarcity due to the time and difficulty expended unencumbering its use, but a more precise characterization would be to say that it impeded both maximizing output and resolving interference.

The primary measure taken to resolve the situation was rebanding, or moving specific users to consolidated bands of spectrum in areas where compatible uses were less likely to create interference for each other. Nextel had effectively re-organized commercial licenses because they could be traded in the market, but regulation prevented similar reconfiguration of public safety licenses. The FCC ultimately adopted, with changes, a plan proposed by a consortium of spectrum users that included Nextel. Had regulations been favorable to doing so, it is likely that rebanding, including of public safety users, may have taken place without direct intervention by the FCC.

This chapter categorizes a range of spectrum management issues that contributed to the circumstances of the Nextel case. Many of these are broad issues that arise, even today, in other contexts. These general issues could often be addressed more efficiently with appropriate provisions in a dynamic policy license than through the use of a traditional license.

Beyond the broad issues, we make the specific argument that from an economic perspective, the dynamic policy license could have been used by regulators in the Nextel case to reduce transaction costs. Reduced economic friction would have enabled maximizing output and minimizing interference in a manner that was more timely and less contentious than the process that ultimately unfolded. Specifically, the dynamic policy license could have eased the rebanding process if all licensees that were party to the Nextel proceedings had been licensed under a DPL. Following the concepts of the thought experiments from the previous chapter, this would have readily enabled repacking of the bands while enabling new assignment models, planned changes, and a flexible response should interference arise.

The dynamic policy license may also have given regulators a mechanism and sufficient comfort to authorize a secondary market for spectrum swaps, with the allowed provisions contained in dynamic policy licenses. Had secondary markets and trading mechanisms existed for all affected licensees, including public safety, the market may have been able to reband and resolve interference with very little direct regulatory intervention. Had public safety been offered uninterrupted operation, minimal inconvenience, and new radio equipment they would likely have agreed. The relocation and equipment costs would have come from the higher output, or additional value, created by Nextel's use of the spectrum. The outcome would have been the same as was ultimately required by regulatory mandate, but easier to achieve.

The historical perspective demonstrates that specific issues continue to exist in spite of, or because of, changes in spectrum use and technology. The dynamic policy license concept would have been useful in the Nextel proceedings, just as it could be useful for fundamental spectrum management issues in the future.

3.1 The Dynamic Policy License, Looking Backward

The dynamic policy license is different from traditional fixed licenses because the regulator retains the option to alter one or more of these parameters during the life of the license. By retaining certain options, the regulator gains flexibility in the administration of the spectrum affected by the license and in the license terms themselves.

While this flexibility may appear to be a drawback from the perspective of the licensee, it is an idea that carries certain advantages. The licensee may gain access to spectrum that would otherwise be unavailable or may gain access to spectrum more quickly than by using more traditional spectrum licensing approaches. Further, if this flexibility is used by the regulator to quickly resolve issues such as harmful interference between users of a band, licensees may see this as a positive feature of the band. Finally, by clearly delineating the scope of the changes, the licensee can be given guarantees on, for instance, the bandwidth assigned to them and limits to the possible changes that facilitates planning from both an engineering and a business perspective. As noted in the first chapter, changes to license terms may be arranged in manner that is enables, and is attractive to, secondary markets. A secondary spectrum market would have avoided, or assisted in resolving, many of the central issues in the Nextel case.

Traditional licensing approaches are conservative because the regulator wishes to consider all possibilities and ensure they are making the right decision. Despite this caution, it is hard to predict future events and consequences, such as the invention of new technologies or applications. With many current services using commodity equipment, a fixed spectrum license is not the key to the service's success. Rather, it is guaranteed access to a spectrum bandwidth within some modest constraints. The DPL enables the regulator to provide these guarantees while retaining the remaining flexibility to facilitate spectrum management. This encourages quicker decisions and better capability to adapt to future changes.

The license has two components designed to assist the regulator in maintaining flexibility while still giving certainty to the licensee. The first element is the **license specification**, which is the framework for the license and contains the entire set of possible parameters that the regulator can choose from for the current conditions and future modifications in the license. At any given time the licensee operates under the second element of the license, a **policy directive**. The policy directive is the set of specific parameters which are in use at that time.

Flexibility is advantageous to the regulator, and at the same time guarantees to the licensee that alterations to the license occur only within pre-negotiated terms. These terms can include not only the allowed changes but also the amount of notice required before a change and the number of times the regulator can exercise their option for change over the life of the license.

The dynamic policy license improves upon the current spectrum management model. Currently, once the regulator grants a license, they have few procedures available to them to change the terms of the license beyond harmful interference proceedings, which are themselves slow and cumbersome. Because the ability to make changes to a license is limited, regulators are conservative about spectrum usage decisions. They allow an extended period for comments and analysis to predict the best solution to an inherently complex situation with many future unknowns. If an undesirable situation arises in the future, considerable time and money must be expended by all parties to the situation to find a resolution. These circumstances and challenges are expected to occur more frequently and be increasingly difficult to resolve as spectrum usage intensifies and the pace of changing technology permits new applications, equipment, and business models. While regulation is ideally intended to foster innovation, in reality, it typically lags innovation. The regulator is left to make difficult decisions about complex technologies in a dynamic and uncertain environment.

The dynamic policy license is not synonymous with dynamic spectrum access. However, one way to implement the dynamic policy license is via a database engine that distributes the license to a policy-based agile radio [48]. This approach is similar to that taken to manage access to television white space [26,59,60] and the Citizen's Broadband Radio Service (CBRS) [16] in the US.

Automating certain aspects of the license via policy-based radios and a spectrum database which manages the license specifications and policy directives is a modern option, but is not required. Creating and administering the dynamic policy license can be as simple as a letter from the regulator delivered to the licensee giving notice of an allowed change under the terms of the license. In the case of Nextel, the process of altering the license terms would have been entirely manual, given the technology of the 1990s and early 2000s. Despite the lack of any automated features, a more flexible license would have assisted with resolving the proceedings more expeditiously.

3.2 Approach

Scientific experiments often permit the empirical evaluation of the effects of an intervention. Spectrum policies rarely have this option. Instead, they must be evaluated based on their anticipated effects. One way to do this analysis is to consider the difference a policy might have made in a previous situation, where a similar situation might occur again in the future.

While we use the case study as the unit of analysis, the intent is not to represent the history of the Nextel case or fully describe the situation and events. Instead, the goal is to understand the underlying themes that continue to affect regulators and other spectrum stakeholders today. The circumstances of the case are used to define categories and subjects more than to explain events, relationships, and motivations. The work is more inferential than descriptive in that it goes beyond the specific situation to consider applications for the dynamic policy license in more generalized situations. The intent is to gain greater insight into alternatives for managing spectrum licensing and making spectrum decisions.

This case provides a rich background for examining different features of the dynamic policy license. One reason is due to the duration of the proceedings. From the time the FCC began its inquiry until it reached a decision took almost five years. The implementation of the decision took more than three additional years.

The proceedings also had many stakeholders and even many classes of stakeholders. The regulator, public safety, Nextel and cellular operators causing interference, private and commercial radio system operators in the affected band, special interest groups such as the Association of Public Safety Communications Officials, equipment manufacturers, license holders in adjacent bands affected by rebanding, a transition manager, and even competitors sensitive to unfair advantages all participated in filing over 2,200 comments.

The case also demonstrates enduring facets of spectrum management, such as the need to accommodate changes in use or technology over time and the need to provide interference monitoring, management, and resolution.

3.3 History and Proceedings

What follows is an overview of the circumstances surrounding the public safety interference problem and the response of the Federal Communications Commission. No attempt is made to cover the details of the progression of the proceedings, but they are available through the references provided. Instead, the focus is on the essential spectrum management issues related to the proceedings. A central theme is that the issues of the Nextel case were created, at least partially, by the effects of regulation, and that they were unresolvable without direct intervention by the regulator. The situation, and measures necessary to resolve it, introduced friction into the spectrum management process, inhibited economic output, and delayed the abatement of harmful interference.

3.3.1 The 1974 Band Plan for 800 MHz Spectrum

Cellular mobile wireless communications arrived in a band plan that never anticipated them. In 1974 the FCC combined a block of government spectrum with channels that had previously been assigned to UHF television in the 800 MHz frequencies and allocated them to so-called Land Mobile Radio Systems (LMRS) [65]. Examples of LMRS system operators include public safety users such as police, fire departments, and ambulances; public works; and fleet dispatch services such as taxis and utilities. In 1979 the FCC defined the term Specialized Mobile Radio Service (SMR) to denote certain LMRS services [66].

While Motorola, Inc. had demonstrated the first handheld mobile phone in 1973, there was no way to anticipate the extent to which consumers would embrace them. Bell Labs patented the idea of frequency reuse via cellular architecture in 1972, a key technology for enabling limited spectrum to serve what would become a significant number of mobile consumers. The first cellular mobile phone standard, known as the Advanced Mobile Phone System (AMPS), was not approved by the FCC until 1983. It is fair to assume that the consumer trends and cellular technologies that became the mobile phone phenomenon were wholly beyond anything the FCC might have envisioned in 1974.

The type of communications system was, in fact, not even considered by the FCC when making the 1974 band plan. Nor the intended use, such as public safety, commercial, or private radio networks. As always, the FCC was concerned about interference in the communication systems. For LMRS, the primary concern was intra-system interference within the same communications service. To avoid this, the FCC assigned channels that were one megahertz apart (i.e. a 1 MHz guard band) instead of assigning contiguous channels. At the time, the FCC believed that inter-system interference between different communication services would not be a problem. Therefore, land mobile radio licenses in the 800 MHz spectrum did not get assigned in channel blocks or contiguous bands as is now common for mobile cellular licenses. Instead, the channels were spread throughout the land mobile band and separated by channels in use by other mobile radio systems. Therefore, public safety, commercial, and private land mobile radio services were all interleaved with each other. There were many different types of services in adjacent channels, or sharing the same channel but geographically separated.

3.3.2 Nextel: New Technology, New Services

In 1991 Motorola, Inc. began development of what would become known as the Integrated Digital Enhanced Network (iDEN). This technology allowed operators to create a mobile trunked radio service with telephone interconnect. A distinguishing feature of the underlying Motorola technology was that the radios were able to operate in non-contiguous radio spectrum. Other cellular mobile services required contiguous blocks of spectrum to function.

Nextel began operations under the name FleetCall in 1987, offering wireless digital communication services to fleet and other dispatch customers. They used specialized mobile radio service (SMR) licenses in the 800 MHz band previously used for analog-based radio dispatch, primarily by taxi operators. In 1993 FleetCall changed their name to Nextel Communications, Inc.

Toward the end of 1996, Nextel Communications began using Motorola's iDEN technology to offer mobile telephone services to the general public, as well as fleet operators. Using Motorola's iDEN technology made it possible for Nextel to utilize their licenses in non-contiguous, interleaved spectrum bands and to combine them in such a way that they could offer mobile phone services. Despite a difference in underlying technology, they were

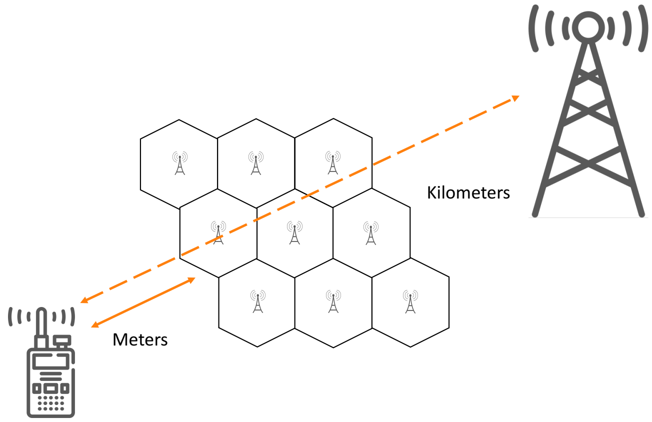

Figure 3.1: The near-far problem, where a nearby transmitter overwhelms the radio receiver and prevents successful communication from the distant tranmitter.

able to provide services that were similar to, and competed with, cellular mobile telephone systems. Due to the additional services offered beyond traditional SMR, Nextel called their services Enhanced Specialized Mobile Radio (ESMR).

3.3.3 New Problems

Beginning in the late 1990s, the FCC began to receive complaints from public safety agencies about interference in their radio communications. Commonly, a police officer or a firefighter would find that they were unable to communicate over their mobile radio if they were near a commercial radio base station operated by Nextel, or sometimes one of the other mobile telephone carriers. Radio problems sometimes occurred even if communications had previously been possible in a specific geographic area or location.

The interference issues were a specific case of the near-far problem, see Fig. 3.1. A public safety radio located near a commercial mobile radio service base station would receive a powerful signal from that base station, making the public safety radio incapable of distinguishing the weaker and more distant public safety base station signal in a distinct but similar frequency band. The problem occurred most frequently in proximity to Nextel base stations because they used frequencies interleaved with the public safety frequencies.

Occasionally, however, interference was caused by other cellular operators using frequencies just above those occupied by public safety through an unintended process known as intermodulation. While the types of interference are not otherwise significant in the discussions of this paper, it is worthwhile noting that stakeholders other than Nextel, operating on nearby frequencies, were also sometimes a party to the interference problem.

3.3.4 Causes of Interference

There were two underlying technical causes for the increasing interference to public safety radios. One was related to the use of cellular architecture by Nextel and the mobile phone companies. The other was related to the decision to interleave different communication systems in the same frequency bands.

Public safety system designs were based on being noise-limited and used an architecture with high base station antenna heights and high transmit power configurations and no frequency reuse. Public safety agencies were able to provide coverage throughout their jurisdictions with one or a few base stations and could simulcast to all locations. This design resulted in relatively inexpensive systems that conserved scarce public funds. Commercial radio dispatch systems, such as for fleets and taxis, were built on similar architectural principles. These were known as **high-site** systems.

When commercial mobile phone systems arrived, they used an architecture designed for interference-limited systems. Frequency reuse was necessary to enable mobile operators to reuse their limited spectrum to meet the consumer demand for mobile phone communications. The resulting, so-called, cellular architecture has many low power base stations and relies on mobile handoff from base station to base station or cell to cell throughout a given geographic area to provide continuous coverage. This design enabled commercial operators to serve many users with a limited amount of spectrum.

As the number of cellular base stations grew, so did the opportunity for interference. Public safety radios were designed to receive low signal levels, almost down to the noise floor. This design enabled them to operate throughout their jurisdiction, even at locations most remote from the single high-site transmitter. This radio design made it difficult for the receiver to reject dominant nearby unwanted radio transmissions, such as from cellular base stations. Cellular base station antennas were also often installed close to the ground to limit interference to nearby cells. Low antennas meant that the cellular base station signals were less attenuated by distance than if the transmit antenna installations were at higher locations. Consumer mobile phones themselves were not a source of interference due to a much lower transmit power compared to the base stations.

The large difference in signal strengths between high-site public safety systems and commercial cellular systems created interference for the public safety systems, even though all systems were operating legally and within FCC limits.

The second problem leading to interference was the interleaved frequency bands. This decision placed the different architectures operated by public safety, commercial, and private radio systems directly adjacent to each other. Public safety radios needed to be able to transmit and receive in any of the designated 800 MHz channels to be able to operate in any public safety system nationwide. It was not economical or practical to build public safety radio receivers that worked only in the specific channels that were unique to each system or jurisdiction. The inability to filter unwanted frequencies left radios open to interference from powerful nearby transmitters.

The 1974 approach taken by the Federal Communications Commission worked as long as all licensees built similar systems. The arrival of cellular architecture resulted in unforeseen incompatibilities and led to interference.

Beyond the technical incompatibilities, the increasingly intensive use of spectrum created increased opportunities for interference. The consumer demand for mobile telephone services created a class and quantity of users that had previously not existed. Public safety use, too, was growing. All available channels were in use in larger jurisdictions and experienced growing traffic volumes. Agencies in congested urban areas complained about having inadequate spectrum for their operations.

3.3.5 Federal Communications Commission Proceedings On The 800 MHz Interference Problem

The FCC formally began investigating the public safety interference problem in 1999. On July 8, 2004, the FCC issued the 800 MHz Report and Order designed to resolve interference in the 800 MHz band [67]. The 800 MHz Report and Order of 2004 had two essential components. The first was the definition of what constituted unacceptable interference, and specific steps to immediately begin mitigating interference to public safety or other non-cellular systems. For the short term, they created technical standards that defined unacceptable interference. The standards enabled a definition of who was entitled to interference protection, particularly in the near term before the long-term rebanding or relocation could take place. They also created procedures that explained who was responsible for mitigating interference if it was detected, and what an operator of a system responsible for interference must do.

The second major portion of the Report and Order involved the reconfiguration or rebanding of systems operating in 800 MHz spectrum to separate public safety and other non-cellular systems from cellular-type technology. In the longer term, the FCC proposed a reconfiguration of the 800 MHz band that was designed to separate the two different types of system technologies. Under the plan, Nextel was required to relocate their operations from the 800 MHz band to spectrum located at 1.9 GHz provided to them by the FCC. The FCC designed a transition plan with three goals (1) minimal disruption to all stakeholders in the 800 MHz band, (2) a mechanism for funding the reconfiguration costs, and (3) to provide additional spectrum averaging 4.5 MHz for public safety communications. The FCC designated a third-party firm as a transition manager for the process. The second part of the plan provided for a 36-month transition for existing users of the 800 MHz band to transition to their new frequency assignments in the band.

Before the FCCs final decision on a resolution, several proposals were put forth for addressing the problem. The Best Practices Guide of 2000 [68] included voluntary measures designed to reduce interference. Nextel published a white paper in 2001 that proposed a rebanding of frequencies as a solution to the problem [69]. In 2002 the FCC issued the 800 MHz NPRM that asked for comments on rebanding and other alternatives [70]. In 2002 a coalition of 800 MHz stakeholders, which included Nextel and some public safety organizations, proposed what they called the Consensus Proposal that included a revised rebanding plan [71]. The final FCC order was heavily influenced by the Consensus Proposal, adopting the proposed overall approach and many of the proposed provisions. In the absence of regulation that effectively prohibited a private market solution to the problem, we may speculate that the market may have been able to resolve the issues with minimal direct regulatory intervention.

Details of the plan included moving Nextel to 14 MHz of spectrum in the upper 800 MHz band, specifically 817-824/862-869 MHz. In the lower portion of the band, 18 MHz was designated at 806-815/851-860 MHz to be used by public safety. Between the upper and lower band areas, so-called expansion bands and guard bands were reserved to separate public safety and ESMR. Nextel was required to give up all of its 800 MHz spectrum below 817/862 MHz. The net effect of this was to provide an additional 4.5 MHz spectrum for public safety use. The additional spectrum was intended to help public safety alleviate congestion and meet their needs for additional spectrum, particularly in larger cities. The pre-reconfiguration band plan is shown in Fig. 3.2, and the post-reconfiguration band plan in Fig. 3.3 [67].

Nextel was required to pay the cost of all relocations for themselves and other incumbents in the 800 MHz band. The FCC Report and Order provided specifics for the administrative, financial, and license details of the band reconfiguration. In exchange for the spectrum vacated by Nextel and incurring the costs to reconfigure the band, the FCC gave Nextel nationwide licenses for 10 MHz of spectrum at 1910-1915/1990-1995 MHz. Nextel

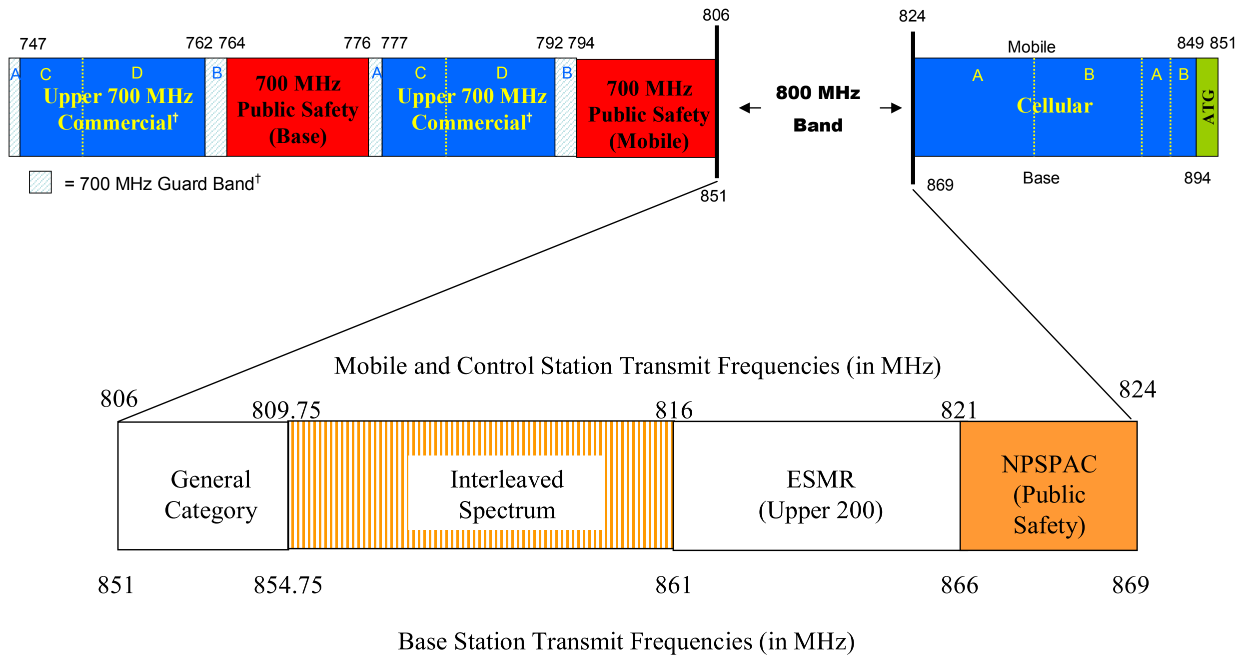

Figure 3.2: Pre-rebanding plan.

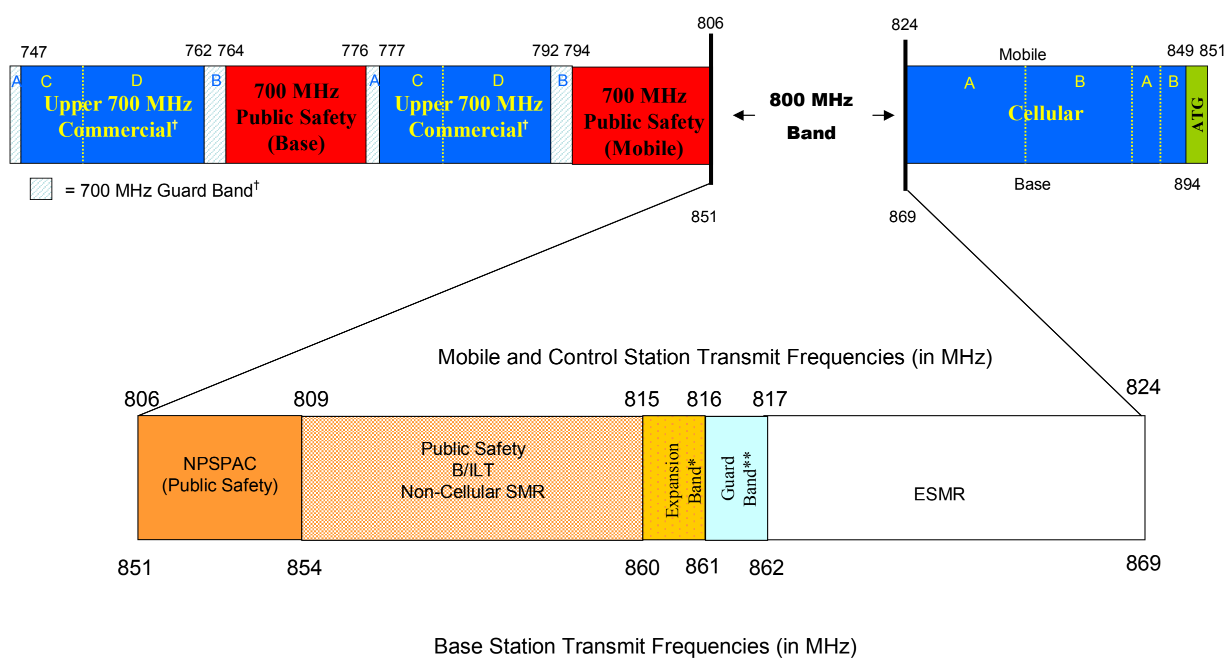

Figure 3.3: Post-rebanding plan.

was ordered to pay to the US government the difference, if any, between the value of the 1.9 GHz spectrum and the spectrum returned by Nextel plus the costs incurred by Nextel to reconfigure the 800 MHz band, and for clearing the 1.9 GHz band. Despite this provision, many cellular operators, such as Verizon Wireless, argued that Nextel was receiving valuable spectrum for less than what it was worth [72–74].

3.4 The Issues

A categorical perspective may be used to consider the issues of the Nextel case. From a Coasian perspective, the first group of categories are largely related to "maximizing output," or spectrum to higher economic and social utility. One of these categories is the change in demand. After the invention of mobile phone services, businesses and the general public began to realize their utility, and there was an explosive growth in mobile phone use. At the same time, there was a more intensive use of public safety spectrum. While these two areas saw increased demand, there was a slow reduction in the use of other services, such as centralized dispatch. Many private and commercial users moved from dispatch-type communications to communications over mobile phones. The change in demand led to changes in use, for instance, the type of communications technology preferred by consumers and businesses. Businesses, in particular, started to prefer mobile phone communications instead of dispatch communications for many interactions. Voice quality was generally better, and it was often desirable to have one-to-one communications instead of one-to-many. Moreover, Nextel offered a push-to-talk service, which mimicked much of the functionality found in dispatch radios when needed.

Changes in technology, such as the introduction of mobile phones, and the introduction of cellular architecture to permit frequency reuse, were specific enablers of new business models, new applications, and new services. The introduction of Motorola's iDEN service was also a technology that enabled new services to be offered using existing spectrum bands and licenses. The changes in demand, usage, and technology highlight the need to enable flexibility to permit a continuous efficient use of spectrum over time. New services like mobile calling required spectrum for an application that had previously not existed. The growth in demand for mobile phone spectrum required cellular architectures so that individual licensees could reuse their spectrum efficiently within their service areas. The regulator is left to deal with the consequences of changes in demand, use, and technology.

More intensive use by public safety also required new spectrum. Following the events of 9/11, there was an increased emphasis on nationwide interoperability of public safety systems that required additional spectrum coordination. In the nearby 700 MHz band additional spectrum was becoming available due to the transition from analog to digital television broadcasting. One of the proposals considered during the Nextel proceedings was to move public safety to the 700 MHz bands. While this move did later become a reality, the option was rejected during the Nextel proceedings because the analog to digital television transition was still years away from being complete. At the same time that public safety and mobile phone consumers were demanding more spectrum, less was needed for commercial and private dispatch services. Certain uses of spectrum, such as for tone pagers, virtually disappeared with the advent of cell phones. Over time spectrum use changed to a higher value. For instance, Nextel found it more valuable to use their spectrum and licenses to offer mobile phone services in addition to, or instead of, private and commercial system dispatch.

The Nextel proceedings also demonstrate a need to manage coexistence between different radio systems. Coase argues that maximizing output, or efficient use of the spectrum is more important than minimizing interference, but both are necessary. In fact, without efficient management of harmful interference, output cannot be maximized.

The incompatibility between high site and cellular technology created a situation that required the intervention of the regulator to resolve. At the time the band plan for the spectrum used by these systems was created, it is unlikely that the regulator could have foreseen the new technologies and radio architectures that were to be introduced or predicted the demand for new services. Therefore, part of managing coexistence is about enabling the ability to alter the status quo in the future in response to changing technologies, demands, and services. Managing coexistence in 1974 meant preventing intra-system interference and interleaving licensees in different spectrum bands, but with the introduction of cellular architectures, it meant managing inter-system interference and grouping like systems, uses, and architectures together with guard bands between them. Over time this required rebanding.

Public safety systems endured interference from at least the mid-1990s until the issuance of the 2004 Report and Order. Even after this, there was a transition period exceeding three years. This period of more than ten years meant that public safety had to endure interference, and all parties had to endure the effort and cost of attempting to mitigate interference on a case by case basis. Nextel had to endure uncertainty as to their future, their technology, and their operations. All involved stakeholders devoted attention and resources to the proceedings that could likely have been used elsewhere more productively. While Nextel eventually had dedicated spectrum for its service they were burdened with rebanding themselves and moving other spectrum users to different bands. Nextel could have otherwise continued to operate with the licenses they owned in their original spectrum, without incurring any additional costs, even if that spectrum was deemed to be less valuable from a market standpoint. The final resolution on rebanding was not particularly palatable to competitors, who complained that Nextel had received spectrum at below market value in what was effectively a private sale. The award of spectrum to Nextel created a different business landscape for the competition. The competitive landscape would likely have been easier for other carriers to negotiate by licensing Nextel under a system where the allowed parameters and changes were predictable. Specific issues can be categorized as follows:

Maximizing Output (Economic and Social Utility):

(1) Change in demand.

- More intensive use of public safety spectrum.
- Increasing demand for mobile phone services.

- Reduction in demand for dispatch-type services. Replaced by cell phones, trunked radio with push-to-talk.

(2) Change in use.

- Sale of taxi dispatch licenses to Nextel
- High site taxi dispatch licenses/services converted to consumer cellular mobile.

(3) Change in technology.

- Introduction of mobile phones.
- Introduction of cellular architecture to permit frequency reuse.
- Introduction of Motorola iDEN to use interleaved spectrum bands.

(4) Need for efficient use of spectrum over time.

- New services, like mobile phones, needed spectrum.
- Need for cellular architecture to allow efficient spectrum reuse by licensees. Regulator needed to deal with the consequences.
- More intensive use of public safety required more spectrum. Post 9/11, had to be interoperable nationwide.
- 700 MHz becoming available due to transition from analog to digital TV broadcasting.
- Less need for commercial/private dispatch spectrum as cell phones became more popular.
- Spectrum use changed to higher value. Mobile phones instead of taxi dispatch.

Minimizing Interference:

(5) Managing coexistence.

- Incompatible cellular and high-sites.
- New and unforeseen technologies and architectures.
- New and unforeseen services.
- Conditions of license approval for Nextel.
- Increase in demand. More intensive use overall.
- New interference standard.
- Interleaving of bands.
- Rebanding.
- Enduring interference.
- Cost of attempting to mitigate case-by-case.
- Opportunity cost of services not introduced due to uncertainty or lack of spectrum.
- Cost of proceedings, and attention required by stakeholders.
- Uncertainty for Nextel.
- Cost to Nextel (new spectrum was not cash flow).
- Change in competitive landscape.

Reducing Transaction Cost (Economic Friction):

(6) Inefficient process

- Many stakeholders.
- Many comments.
- Many alternatives and proposals.
- Long.

- Complex.
- Costly.
- Enforcement, compliance, and ongoing monitoring.
- Transition manager.
- Time/difficulty of clearing spectrum and implementing rebanding.

The proceedings overall call for a process that is more efficient and expedient. The proceedings affected many stakeholders and were long, complicated, and costly. They ultimately required the employment of a transition manager. Once the report and order was issued, there was time, difficulty, and expense incurred in clearing spectrum, rebanding, and moving all of the affected parties to their new spectrum bands. Parties to the proceedings expended effort proposing and considering the pros and cons of different alternatives along the way. The issues in the Nextel case, while specific instances of certain circumstances, were indicators of more general categories of challenges to spectrum management that are still faced today.

3.5 Applying The Dynamic Policy License

Because of its flexibility, the dynamic policy license is designed to be able to respond to a more vibrant spectrum management environment. For instance, changes in technology, demand, and use related to maximizing output of spectrum utility affected Nextel, public safety, the regulator, and all related stakeholders. By issuing licenses that permit the regulator to exercise certain flexibility when necessary, these changes could be better managed.

Perhaps, for instance, anticipated future demand for a service is, in fact, less than expected. The result is that spectrum allocated for that service is underutilized. If the spectrum were reallocated more quickly to services experiencing greater demand, it would be advantageous to both system operators and end users. In a similar circumstance, technology allowed FleetCall/Nextel to offer new mobile calling services with no loss of capability to also provide dispatch services. Similarly, the transition from analog to digital television broadcasting produced a digital dividend of available spectrum. Having an efficient process to reduce the friction of responding to changes would also make the job of the regulator easier. In the case of the Nextel proceedings, this may have made it simpler to clear spectrum during the rebanding process.

The Nextel proceedings highlighted the need to manage coexistence, which often requires the involvement of the regulator. If they have the flexibility to direct how and where spectrum is used without time-consuming and expensive proceedings, and with the prior agreement of involved parties on the extent of their options, they are better able to manage the coexistence process. For instance, in 1974, the interleaved band plan made sense. If the regulator had reserved the right to repack these bands should that be necessary, then they could have administratively reconfigured the different uses, perhaps at the time that Nextel was purchasing their licenses or changing the utilization of the licenses, and it may have been possible to avoid the interference proceedings altogether. Further, with greater future flexibility, the regulator may have allowed licenses that were more flexible for the licensees as well. Provisions could have allowed greater freedom to trade spectrum and voluntarily reband, with only minimal involvement by the regulator so long as the market solution was effective.

Changes in use are another area where flexibility would be beneficial to the regulator. For instance, the FCC might have initially permitted public safety to utilize a single high-site transmitter to cover a jurisdiction but reserve the option for them to install additional lower power transmitters to make it easier for other systems to co-exist. Similarly, Nextel may have initially begun with relatively few base stations, but as demand grew and spectral reuse requirements became more intensive, it would have been advantageous for them to know that they could change their system density and architecture as necessary to meet demand.

Further, while not demonstrated in the Nextel case, the flexibility to change use may be advantageous. For instance, had Nextel been unable to purchase taxi dispatch licenses to offer more general commercial services, or had they been unable to use their dispatch licenses for mobile phone-like services, the public at large would have missed out on the benefits of mobile competition and choice. The spectrum would not have moved to its highest and best use. Therefore, a licensing framework could take advantage of the flexibility to respond to changes in demand or usage patterns without a complex regulatory process.

It is clear that changes in technology will continue to occur. In fact, the wireless industry depends upon this fact to manage more intensive usage of all spectrum and the demand for new services by consumers. It is also evident that many changes in technology are unanticipated. For instance, it is difficult to predict what has yet to be invented. Therefore, a licensing or spectrum management system that can respond at the same rate at which technology develops is needed. If the pace of technological change is rapid, but changes in spectrum management are slow or static, then new technology that assists in managing the spectrum crunch or that may be desirable and advantageous to consumers can take a long time to implement, if it is possible to do so at all. Therefore, any spectrum management system or license that responds better to the rapid pace of technological change is advantageous.

Congruent with the writings of Coase, the regulator has a duty to ensure that spectrum is used efficiently over time. As technology, demand, and uses change, the regulator must be able to change the licensing system to efficiently manage the spectrum and account for these changes. The need for efficient spectrum use drives innovation, but also creates more opportunities for interference. The regulator must be able to deal with the consequences of this interference while having a system where incremental changes and testing can take place with adjustments as required.

A different framework for the analog to digital television broadcast transition that took place in the 700 MHz bands and below might have had a fundamental impact on the Nextel proceedings. If the regulator had a system to manage this transition more quickly then the available spectrum might have been efficiently placed in use for public safety at 700 MHz perhaps a decade earlier than otherwise happened. Instead of rebanding several services within 800 MHz and 1.9 GHz, it might have been possible to move public safety directly to 700 MHz. This capability would have saved many steps in the Nextel proceedings and made the rebanding and transition easier. Likewise, as certain services such as voice and tone/alphanumeric paging lost users and popularity, it would have been advantageous to be able to rapidly reassign this spectrum to higher uses with greater demand.

A faster and more flexible process would be beneficial to licensees, and the license specifications would provide them more certainty than the unknowns of a regulatory inquiry and proceeding. They would ultimately have the advantage of a better-defined process with better options, a clearer idea of what costs they might incur and when, and the range of possibilities that they might be facing. The regulator would benefit from a more flexible, less contentious, less costly, and less time-consuming process, and would likely find their enforcement, monitoring, and spectrum management duties eased. They would also need to be less concerned about considering all possible alternatives and could instead focus on the alternatives that were laid out in the license specification.

A dynamic policy license would provide clear benefits to both the regulator, the licensee, and likely to related stakeholders. A dynamic policy license is a means to reduce transaction costs and economic friction. To this end, it helps to maximize output and minimize interference. Using such a license could perhaps have avoided many of the issues faced in the Nextel proceedings, and even if the events had transpired, it might have more readily provided a path for resolution of the issues.

3.6 Looking Backward and Forward

Since the 2004 proceedings, there have been many more changes. Sprint acquired Nextel in 2005, and rebanding continued under Sprint. Nextel's iDEN network was shut down as of 2012 and Sprint is using the spectrum formerly licensed to Nextel for deployment of their LTE networks. These changes demonstrate the pace of changes in technology, use, demand, and even business processes. The transition manager still exists today, available to assist in resolving any complaints of interference that may occur.

Negotiations continue around rebanding and cross border coordination, which is to say that cross border coordination is an issue that remains unresolved some 20 years after the start of the interference problem. International affairs cannot be resolved unilaterally through the application of the dynamic policy license. However, if regulators on both sides of borders utilized a dynamic policy license they may both find they have additional flexibility and fewer coordination challenges and can perform cross border coordination more readily. Further, many of the underlying issues that existed in the Nextel case often arise across borders between countries, where resolution is even more challenging and involves not only regulatory agencies but also the Departments of State.

The issues in the Nextel case are not unique. Many other well-known interference disputes exhibit similar challenges. Examples include defense spectrum users interfering with garage door openers [75], and the LightSquared network proposal that ultimately failed due to, among other reasons, interference concerns [76].

In the case of Nextel, automated management of license specifications and automated policy directives were not possible due to the lack of policy-based radios and spectrum databases at the time. This is not so much a limitation of the license as it is an expression of the increased capabilities for applying the license that exists today.

There are, of course, situations that the dynamic policy license cannot assist in resolving. For example, while it may provide flexibility for dealing with events in the future related to technology, usage or demand, it does not help with predicting what those events will be. Nevertheless, the regulatory flexibility afforded by the dynamic spectrum license would prove useful across a range of enduring spectrum management challenges. From an economics perspective, the DPL is a means of reducing transaction costs, or friction, when responding to change. To this end, it contributes to the goal of maximizing spectrum output.

Chapter 4

Spectrum Management With the Blockchain and the Dynamic Policy License

Looking ahead, demand for spectrum resources will only continue to grow. For instance, billions of Internet of Things devices, being primarily wireless, will need to access and share spectrum. In this chapter we propose automating the dynamic policy license as a **smart contract** running on blockchain technology. The automated dynamic policy license would assist with managing shared spectrum, even across borders. Consistent with the notion of looking to the future, the ideas are largely conceptual, drawing on a range of technologies and policies that exist but are not yet well developed. Even so, the chapter demonstrates that the dynamic policy license can adapt to new technologies and situations to provide new approaches to managing spectrum.

4.1 The Internet of Things

According to Gartner Research, there were 6.4 billion interconnected IoT devices in 2016, with a forecast for 21 billion by 2020 [77]. A widely-quoted Cisco report places the 2020 estimate at 50 billion interconnected devices [78]. Benefits are expected to extend to a broad range of applications, from smart homes and cities to autonomous vehicles.

The International Telecommunication Union (ITU) provides one definition of the IoT:

Internet of things (IoT) A global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies.

> Through the exploitation of identification, data capture, processing and communication capabilities, the IoT makes full use of things to offer services to all kinds of applications, whilst ensuring that security and privacy requirements are fulfilled [79].

The Internet of Things consists of several layers as shown in Fig. 4.1.

(1) End node devices are used primarily as sensors or actuators that interface with the physical world.

(2) Rather than connecting directly to the network infrastructure, most devices will connect to gateways that serve as intermediaries between the sensor nodes and the network. Depending upon the intelligence of the sensor node, gateways may provide device management and security in addition to connectivity.

(3) The network infrastructure is composed of connection and aggregation points, and routing capabilities for managing data flows.

(4) A cloud infrastructure stores and manages the data generated by the sensor nodes, and will be used to provide computational and analytical capabilities for the vast data streams produced.

In this chapter, we propose a smart contract running on a blockchain platform that assists devices in appropriately accessing radio spectrum. The smart contract and blockchain platform form part of the cloud infrastructure, managing the end devices themselves in addition to their data. In this example a gateway is not used, rather, end devices connect to the network infrastructure directly, facilited by a dynamic policy license.

Functions required for an Internet of Things network include communications, autonomous device configuration and coordination, and distributed sharing of device configuration parameters and data. These must all take place securely.

One challenge to the economical deployment of the large number of IoT devices expected is the heterogeneity of devices and capabilities, along with the heterogeneity of net-

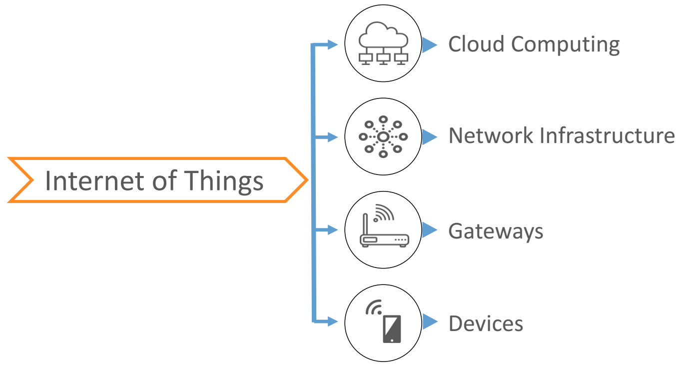

Figure 4.1: Internet of Things infrastructure layers.

works over which they must function. Internet of Things devices are projected to range from so-called smart dust with virtually no storage or computational capabilities to powerful cognitive devices able to connect to many networks and do their own processing and analysis of much of the raw data generated. Other challenges include a lack of common protocols and standards. Security is also a concern. Most nodes need to be uniquely identifiable, and devices must pass authentication and authorization checks before joining or sending data over networks. Identification, authentication, and authorization must take place automatically, and scale to billions of IoT devices. New IoT applications continue to develop in areas where device security is not well tested and may have unanticipated problems. IoT systems may be poorly designed or implemented, particularly given the number of small manufacturers and application developers attracted to the promise of the IoT. Smaller firms may not be aware of good security practices, or may not have the resources to incorporate them into their designs and systems. Lack of security and privacy are ongoing issues in IoT deployments, and devices are notoriously easy to compromise [80]. The security challenge is further complicated when limited processing power and storage capabilities on devices do not permit sophisticated security measures to reside locally.

Network devices have, so far, relied upon a client server model where centralized servers handle identification, security, and communications. The server is required to have substantial computational and storage capabilities, and it will be difficult to scale the client server model to support the size and security requirements of the future IoT. Infrastructure, connectivity, and maintenance in the current model are also too expensive to support the vision of the future IoT. Decentralized IoT networks with peered communications are one possible solution to enabling the IoT to scale. A decentralized architecture has the additional benefit of preventing single points of failure. A peer-to-peer or decentralized model is also a step toward sharing resources, which is one way to reduce costs. Sharing resources may include sharing devices, platforms, resources, or data across many applications and networks.

4.2 Background

4.2.1 Sharing Spectrum

In order to support the large number of IoT devices expected, connectivity and communications, at least at the network edge, will need to be primarily wireless. For this to take place at scale, devices will need to share spectrum. The U.S. President's Council of Advanced Science and Technology (PCAST) report, among others, suggests developing new ways of thinking about sharing, managing, and using wireless spectrum [3]. Similar proposals are under discussion in Europe and other parts of the world [81]. Regulations have been enacted to enable spectrum sharing in television white spaces [26, 59–61], and the Citizens Broadband Radio Service (CBRS) in the 3.5 GHz spectrum [16].

For the application in this chapter we automate the dynamic policy license as a smart contract on the blockchain. However, it still consists of the same two components (1) the license specification, and (2) the policy directives. The **license specification** is the framework for the license. It consists of the possible sets of parameters that the regulator can direct the licensee to use, the conditions under which the regulator can make changes, and other standard licensing terms (e.g. whether the license is transferable). The specific parameter set to be used by a licensee is communicated via a **policy directive** from the regulator.

The regulator gives an initial policy directive at the start of the license, and the regulator can issue subsequent policy directives over time to modify licensee operation and manage the use of the spectrum.

Following an explanation of the background concepts, an example of how the license could function is proposed in Section 4.4, using a dynamic policy license mechanism based on a smart contract running on blockchain technology. This mechanism could be used to securely distribute dynamic policy licenses to Internet of Things devices and manage license parameters, in addition to providing other services.

4.2.2 Policy-based Radios

Policy-based cognitive radios, or just policy-based radios, are radios whose operational parameters are determined by so-called policies that specify permitted and prohibited sets of operational parameters as detailed by, for instance, Fette [48]. At any given time the radio may hold one or more policies. The policy-based radio then reasons which permissive policies allow it to operate without impinging on any prohibitive policies. Policies have a defined duration, similar to the time-limited lease concept advanced by Chapin and Lehr [49].

More flexible radios are one means to permit more flexible spectrum use. The ITU in its 2012 World Radiocommunication Conference, [45], and in its Recommendation 76, [46], recommended that regulatory administrations actively participate in studies on the deployment and use of cognitive radio systems. Resolution ITU-R 58-1, [47], encourages study in the use of cognitive radio systems, with particular attention to enhancing coexistence and sharing among radio communication services.

4.2.3 Spectrum Databases

Countries around the world continue to experiment with dynamic allocation of the so called television white space frequencies vacated when television broadcasting changed from analog to digital. All regulatory domains that have enacted regulations for television white space use depend upon a spectrum database to track available spectrum and incumbent users entitled to protection from interference by secondary users [82]. Devices desiring to use spectrum communicate with the database to announce their capabilities and needs. The database then assigns spectrum, when available, and operating parameters to the device [83].

The database records information about the spectrum in use, other users, and specific device information such as the geolocation, antenna height, maximum power, periods of operation, and regulatory requirements devices must follow. When contacted by a device, the database performs any necessary authentication, then sends the device the regulatory rule set to follow and available spectrum it can use. If there are changes to the availability of spectrum, the database informs the devices in the affected geolocation area about those changes.

4.2.4 The Blockchain

There are now good explanations of blockchain history and function, such as by Narayanan et al. [84]. Therefore, an overview of only the essential features follows as shown in Fig. 4.2. The blockchain was proposed in 2008 by an unknown individual or individuals using the pseudonym Satoshi Nakamoto [85]. The original intent was to create a new cryptocurrency called Bitcoin. A cryptocurrency is a digital or electronic currency that has no physical form and relies upon cryptographic conventions for security.

The role of the blockchain in the Bitcoin proposal is to form a decentralized peer-to-peer network of nodes that provides a shared ledger of all Bitcoin transactions. The blockchain provides integrity, security, and privacy for all participants in transactions, despite the fact that there is no trusted central authority. Blockchains rely on cryptography and principles of game theory to ensure that a cryptocurrency token or other digital asset cannot be duplicated (spent twice), and that the network continues to function correctly even in the presence of malicious nodes, so long as these nodes do not form a coordinated majority on the network.

The blockchain itself is also a digital record, or ledger, of all transactions that have

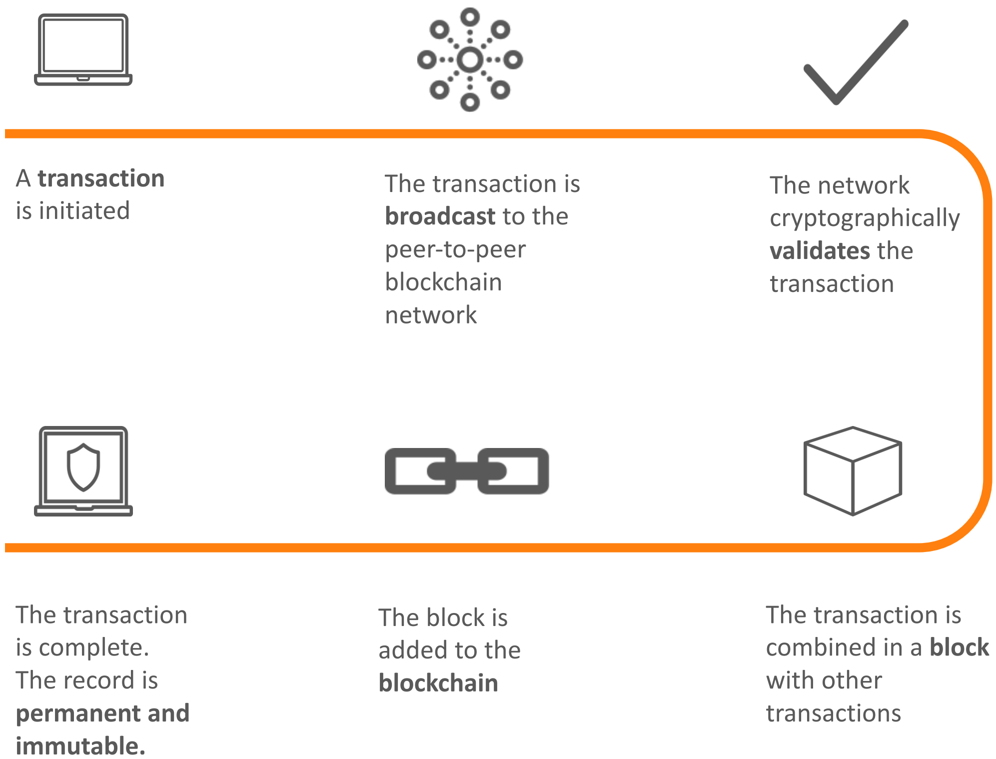

Figure 4.2: How the blockchain works.

occurred since the creation of the first Bitcoin token. The ledger is append-only and relies on cryptographic principles to ensure that the transaction history cannot be altered or erased. Transactions, once verified by the network as being in accordance with blockchain protocols, are written to the ledger to maintain a consensus view of all events leading to the current state of the network. The record of transactions is itself unencrypted and may be searched, thus providing a record that is transparent, auditable, and verifiable in addition to being secure.

Transactions are grouped, along with related information necessary for processing, and the entire group is cryptographically hashed to form a **block**. The hashing property ensures that alteration of even a single bit in the block changes the hash value and will be detected by the network. Each new block includes a reference to the hash of the previous block and a timestamp, thus forming a chain of blocks, or **blockchain**.

The blockchain protocol automatically verifies that transactions meet the rules of the protocol; otherwise, the transaction is not included in the block. The protocol also has mechanisms for resolving conflicts, and for determining which node in the network will write the next block in the blockchain. As a distributed peer-to-peer network, a copy of the digital ledger, or chain of blocks, is maintained on each node in the network. Each node can see the history of all transactions, compare hashes, and verify that the record they hold agrees with the majority of other nodes on the network. Each node can also verify the correct processing and validation of the most recent block.

Each user on the blockchain generates a public/private key pair. Every transaction on the blockchain ties to a cryptographic hash of the user's public key and any assets recorded on the blockchain (Bitcoins, originally) can only be unlocked or spent by using the unique public key of the current owner of the asset. In the original blockchain, key pairs do not associate with a real-world identity, so the Bitcoin network is said to be pseudonymous. This feature appears in some alternative blockchain-style networks, and in others, the keys correlate with real identities.

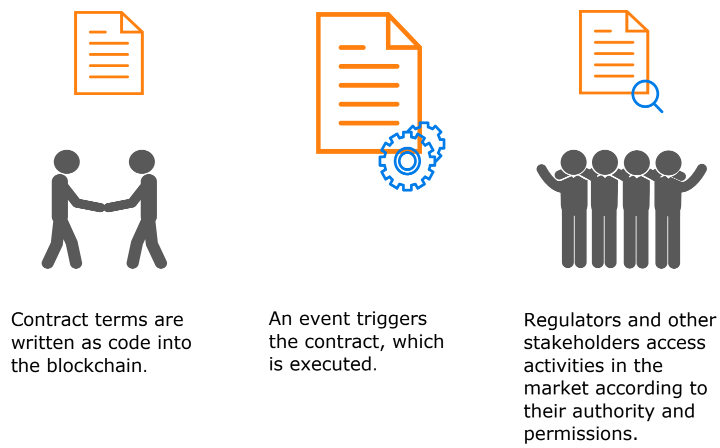

Figure 4.3: A smart contract.

Blockchains have the potential to allow trusted transactions between parties, even at arms-length, without an intermediary of confidence. They also hold the possibility for automating certain processes, such as distributing spectrum policies. They may reduce transaction, record-keeping, and reconciliation efforts and costs while preserving security, privacy, and trust. There will be many new opportunities to apply blockchain technology, including uses for spectrum and the Internet of Things.

4.2.5 Smart Contracts

A smart contract is a decentralized computer program that stores rules for the terms and conditions of a contract, see Fig. 4.3. Thus it controls the transfer of digital currencies or other digital assets between parties. In addition to defining the rules, a smart contract will automatically verify the contract, execute the agreed terms, and enforce penalties in a transparent and conflict-free manner [86]. Christidis notes that there are already systems that work like simplified smart contracts, e.g. a vending machine that exchanges a can of soda for some coins through an established and quickly executed contract [87]. Smart contracts are more powerful, extending the ability to perform more complex transactions over longer term events, and can run on the blockchain.

4.3 Blockchain and the Internet of Things

The blockchain is a good fit for the Internet of Things because it has capabilities that meet many of the requirements for the Internet of Things. Because of the natural fit between these two technologies, blockchains are already in use for IoT applications. Christidis and Devetsikiotis look at a range of industries, applications, and synergies such as smart locks and alternative energy [87]. Within this framework, the idea of including spectrum management is an obvious extension of blockchains and the IoT working together, although it is has not received much previous exploration.

Most Internet of Things devices will require a unique identity. This identity could be an IPv6 address, a MAC address, an eSIM card, an IMEI, a public/private key pair for use on a blockchain, or some combination of the above. Device configurations, licenses, data, and transactions will require security, confidentiality, integrity, availability and related properties like accountability and auditability.

The interconnected and shared nature of devices, spectrum, networks, and data means that multiple stakeholders will be involved. There will be many devices, many stakeholders, and a need for connectivity at different levels. Stakeholders may have complex relationships, business requirements, and contractual obligations, and will not have interests that are always aligned. The heterogeneity of devices means that multiple parties are likely to need to be able to have input on configuring and maintaining devices, and other parties such as regulators will need to have input on acceptable use. The blockchain enables confidential transactions while permitting transparency for stakeholders that require it.

Internet of Things devices will need to operate in multiple geographic and regulatory boundaries, and even move between these boundaries. The large number of devices will require that interactions happen largely autonomously and automatically, as most transactions are anticipated to be machine-to-machine. Automaticity requires a way to encode behavior, transactions, and records on a secure, trusted platform available to all authorized stakeholders. Properties such as the time limitation of spectrum licenses [49], or the revocability of directives causing interference are examples of the parameters subject to management.

The IoT will require physical devices to participate in transactions and automatically record the results. It will be necessary for devices to report their capabilities and status, and for a record of the states to be maintained. The Internet of Things, by definition, takes external inputs from the environment. Keeping a record of these inputs on the blockchain maintains evidence if, for instance, a conflict or dispute requires resolution.

In the Internet of Things, the primary product will be data, and transactions will be the main unit of interaction. Data will need to be validated, transactions will require reconciliation, and many of these interactions will need to be regulated. It may even be desirable to include a Bitcoin-inspired machine currency token in blockchain transactions. The token would provide for a standard unit of value transfer, and enable IoT devices to sell things they have, like data, and buy things they need, like spectrum, without human intervention.

The Internet of Things must be trustworthy, a goal promoted with a transparent and auditable record of transactions and interface information flows. Public transactions must be visible to all authorized stakeholders, while individual stakeholders should have the capability to make private transactions. By maintaining a secure and reliable record of the Internet of Things, the blockchain can reduce search and information costs, reduce bargaining costs, and reduce monitoring and enforcement costs. It also provides visibility into the network for things like service level agreements.

Smart contracts can run on top of the blockchain, and policies such as spectrum licenses are representable as computer code. This code can be embedded on the blockchain and executed based upon predefined inputs. The contract is signed and verifiable, and the records of the contract and all state changes kept on the blockchain. With the terms of the contract encoded in a programming language, smart contracts are said to be self-enforcing, as the code will only execute the instructions agreed to by the parties to the contract. The blockchain, if desired, enables a complete history of all contract parameters and transactions, along with timestamps. The information is available to all authorized stakeholders, even those with different or conflicting goals. The blockchain, therefore, promotes transparency, trust, and confidence. It can enable new business opportunities and relationships, such as leasing or subleasing spectrum. Device management and sharing at many levels via the blockchain enables better accuracy and lower cost. It also enables device autonomy as smart contracts can automatically communicate, and update and record their state transitions on the blockchain.

Some of the functions mentioned previously are available in traditional databases, but even distributed databases still do not offer all features of the blockchain. For instance, with traditional databases, database owners or administrators must be trusted not to modify or suppress data in the database. Traditional databases have a single point of failure, which is also a security risk. Even distributed databases require procedures for recovery. Traditional databases involve the use of many technologies, and each of these has security and integration costs. Traditional databases are only visible at the local database level, whereas the blockchain is globally visible and transactions are immutable. The lack of centralization distributes risk, and the system is robust even in the face of malicious nodes. A standard, secure, technology lowers costs for integration, transactions, and reconciliation.

Internet of Things devices will be responsible for processing much of their own data, or filtering data generated by their peers. Processing transactions using a standardized peer-to-peer model will enable the operations generated by billions of devices. By pushing computation to the edge, costs are likely to be lower than building and maintaining large central data centers. Distributing computation and storage across billions of devices and nodes harnesses the distributed power of the Internet of Things for edge computing. This model prevents failure of any single node on the network from having a substantial impact on the rest of the network.

This communications model will, however, require good security. Devices will need to have a method of identification and authentication, and sensitive data will need protection.

Security and privacy will require validation and consensus for transactions and data flows. The blockchain enables a way to address privacy and reliability concerns on the Internet of Things. It is capable of tracking and coordinating the billions of IoT devices connected to the network, and of tracking the transactions between devices. The Internet of Things network and interactions can be secure and trustless, similar to the way that financial transaction messages currently operate on the Bitcoin blockchain. The blockchain enables automated machine decisions, machine identities and certificates that are secure and transparent, and membership in networks and groups that are independent or distributed. The blockchain also enables management of digital assets like identity, registries, data, machine currency, rights, goods, or resources. Spectrum sharing is an example of the automated management of digital assets enabled via smart contracts running on a blockchain. As there will be many blockchains in the future, transactions will ultimately take place across not only many devices and networks, but many blockchains.

By adopting the blockchain, regulators would not need to be directly involved in most spectrum assignment decisions; just publish the guidelines or rules to automate the assignment process. This model would reduce regulatory workloads and enable spectrum to be put to use more quickly and utilized more efficiently. The regulator could have access to a larger set of data about devices than is currently possible. This data could assist with the traditional functions of monitoring and enforcement, a possibility explored by Malki and Weiss using the blockchain [88] and could enable making future spectrum decisions based upon a more informed, data-driven basis. Device specifications, configuration, and usage information could be made accessible to the regulator or any other authorized stakeholder.

A blockchain-based ledger could meet regulatory requirements for tracking devices, maintaining records, and automatically provide regulatory compliance data. The blockchain, being a shared ledger, could reliably record all devices, configurations, and processes. The regulator, like any other authorized stakeholder, could provide input to device policies. Auditability is particularly helpful where no single entity owns the device, the data, the spectrum, or the configuration. Multiple parties could keep a history of devices, events, and data, even if the parties have contrasting or conflicting goals related to the operation of the device. A blockchain-based system is a more efficient method of maintaining and tracking data than if each stakeholder had to keep separate records and reconcile them with other stakeholders. The single, transparent, centralized record serves to enhance trustworthy interactions between the stakeholders.

4.4 Blockchain-Assisted Cross-Border Spectrum Access for the Internet of Things

Given the trend toward spectrum sharing and the number of IoT devices that need to connect wirelessly, there must be an automated means to distribute licenses and ensure that they are authentic and secure. Once distributed, licenses must be capable of being updated and managed, and there must be a mechanism for monitoring and enforcement of license terms to ensure that spectrum is available without unacceptable interference for all potential users. We use the scenario of an IoT device tracking a shipment of coffee beans from Rwanda to Italy, Figure 4.4, to conceive one way to do this.

Most countries do not yet have shared spectrum regulations or databases. We expect spectrum sharing to become the norm, and for appropriate regulations and infrastructure that supports sharing to develop. This work assumes the general availability of such databases and develops the related concept of using these databases and a blockchain smart contract to manage spectrum assignments and other functions for certain IoT devices.

4.4.1 The Scenario

We propose a supply chain management example where an IoT device monitors the location, temperature, and humidity of a coffee shipment from coffee growers in Rwanda to a coffee processing plant in Italy. Coffee is one of the primary agricultural exports for Rwanda, and Trieste, Italy is a major center for the coffee trade. It is a real example in the

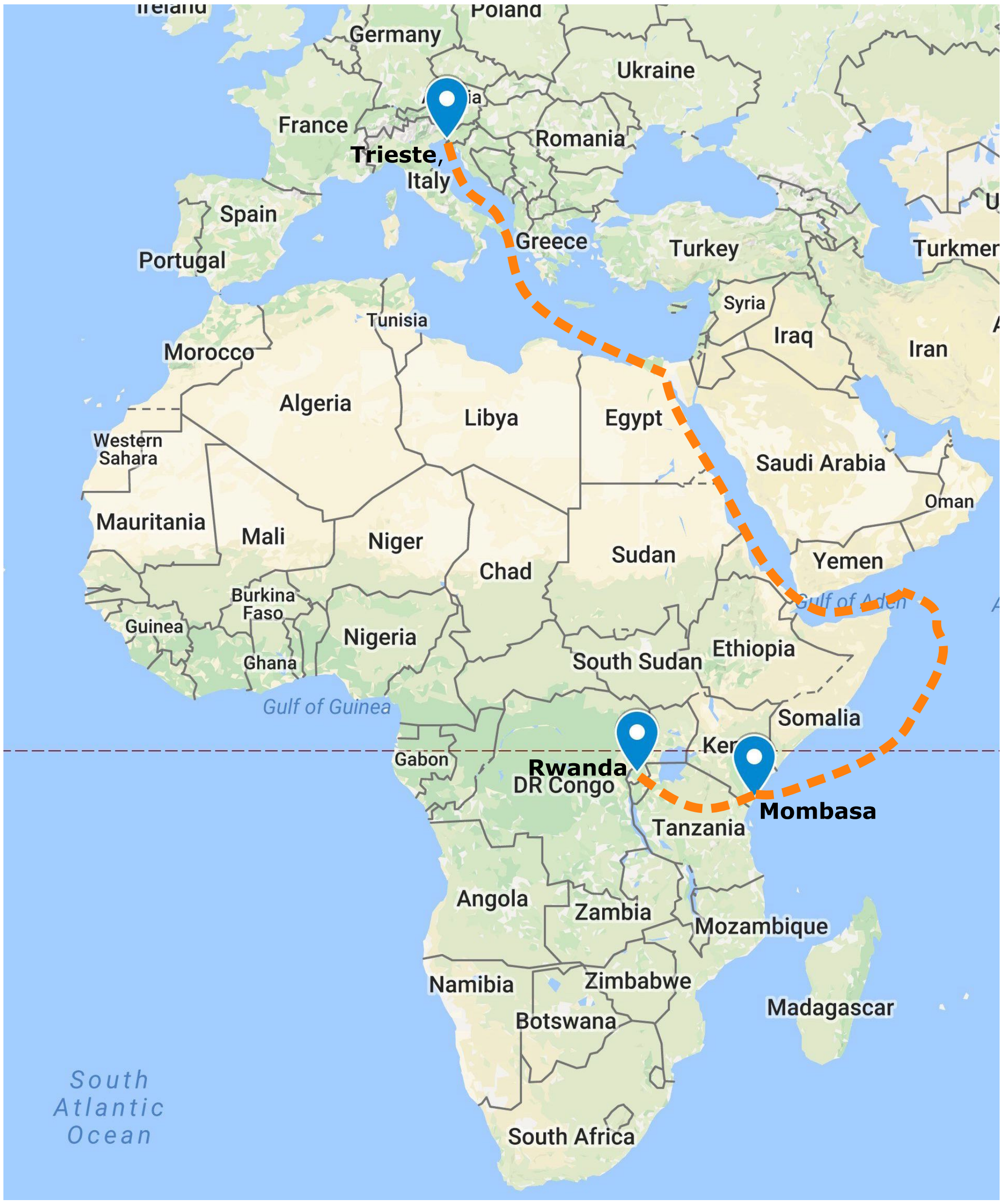

Figure 4.4: Shipping coffee from Rwanda to Italy.

sense that excessive humidity is the primary risk factor leading to damage of coffee beans during shipment. Humidity is dependent on storage and ventilation conditions, the coffee washing process, and the ambient temperature and humidity. Shipping from a hot, humid climate such as Africa to a temperate climate during winter is known to be particularly problematic [89]. The point of the example is not to record the sensor measurements, however, but rather to assign shared spectrum across borders to enable the IoT device to perform its intended functions.

Our IoT device travels with the shipment and must be able to connect wirelessly under multiple protocols and frequencies. Cross-border coordination is required to operate under different regulatory regimes. A smart contract running on the blockchain enables this, acting as the single point of contact for the device and a pre-configured intermediary for interacting with the different regulatory databases. If the IoT device is unable to communicate with the smart contract, or receive operational parameters from a spectrum database, the device will store its data for future transmission.

We consider an advanced IoT device that could track an entire shipping container of coffee. It would have sufficient power, a GPS, and a policy-based radio. Many small and inexpensive IoT devices would not meet these requirements, but their use of radio frequencies is likely to be localized, and they would not need licensed spectrum or an agile radio.

Stages of the coffee transfer process are as follows, and as shown in Fig. 4.5.

(1) Coffee travels from the grower in Rwanda to the local market (normally a washing station) via, say, bicycle. This stage will not be monitored in this example but could be relevant for a different example, like tracking potential conflict minerals. When the coffee reaches the washing station, monitoring by the IoT device will start.

(2) Coffee is transported from the local market to a broker in the main city of Kigali via truck. The IoT device monitors and records the desired parameters. The sensor data recording and transmission processes are not considered in this example.

Figure 4.5: Coffee transport scenario.

(3) The coffee shipment travels via a container on a truck from the broker in Rwanda to a seaport at, say, Mombasa, Kenya. To reach the port, it must travel through either Uganda or Tanzania. The IoT device must adjust its operating parameters as appropriate to conform to the regulations of each country.

(4) The container with coffee travels in the hold of a ship from the port in Kenya to, say, the port of Trieste in Italy. During its journey, it may pass near enough to the coast of a country to connect to a terrestrial base station or may do so when passing through a gulf, strait, or canal.

(5) The coffee is transported via truck from the port to a local processing plant in Italy and unloaded, where tracking ends.

4.4.2 Considering Spectrum Needs and Uses

It is not currently practical or economical for IoT devices deployed in large numbers and mobile anywhere in the world to operate under traditional fixed spectrum licenses. Even if it were practical, it is difficult to match the ease with which devices that use "open" industrial, scientific, and medical (ISM) bands roam and connect to available networks. Ease of use and coordinated spectrum bands have enabled inexpensive devices and an unprecedented number of wireless applications.

Open spectrum works because device transmit power is limited. Low power restricts the range over which devices can communicate but also limits the potential for interference between a large number of uncoordinated devices. Limited range precludes many IoT applications, so in addition to the requirement to easily access spectrum, another desirable characteristic is the ability to transmit over medium to long distances. A Wi-Fi system will have a range of 100 meters or so. If the IoT device were further than this from the access point, it would have to store data until it could connect again, and this is not always desirable. In the case of humidity monitoring for coffee, near real-time information permits action to be taken to prevent spoilage. This situation is preferable to one where stored information from the IoT device is used, belatedly, to assign responsibility or liability for spoilage that has already occurred.

Using spectrum that is not licensed to, say, a proprietary mobile carrier has an advantage in cost and flexibility. It is intended to operate like "super Wi-Fi" that is free and available all over the world without needing a SIM card that ties it to a local carrier network. Television white space frequencies from 470 MHz to 786 are becoming the first global model for free, shared access to long-range spectrum. A means to manage interference is necessary because higher transmit powers are allowed, and the spectrum has excellent propagation characteristics. Greater range increases the number of devices that can interfere with each other, and the television white space model must also prevent interference to nearby incumbent television transmitters. In countries that have enacted white space regulations, a spectrum or geolocation database manages spectrum and radio parameters.

If an IoT device can use spectrum assigned by a database, it must have a means of communicating with the database initially to determine what frequencies and radio parameters it is allowed to use. For this example, the IoT device connects to the Internet and a blockchain-based smart contract that then mediates the negotiations with the spectrum database. For the initial Internet connection, we envision using the LoRa or SigFox protocols in the ISM spectrum bands. These protocols have longer range than other ISM protocols such as IEEE 802.11, but this comes at the expense of being limited to a low data rate.

- LoRa supports data rates ranging from 0.3 kbps to 50 kbps with a range of 2 to 5 km in an urban environment and 15 km in suburban conditions [90] [91].

- SigFox supports data rates ranging from 10 to 1,000 bps with a range of 30 to 50km in rural environments and 3 to 10 km in urban conditions [92].

Wi-Fi could also be used if the IoT device was in the range of an access point. Once the IoT device receives its frequency and parameters, it is advantageous to switch to frequencies

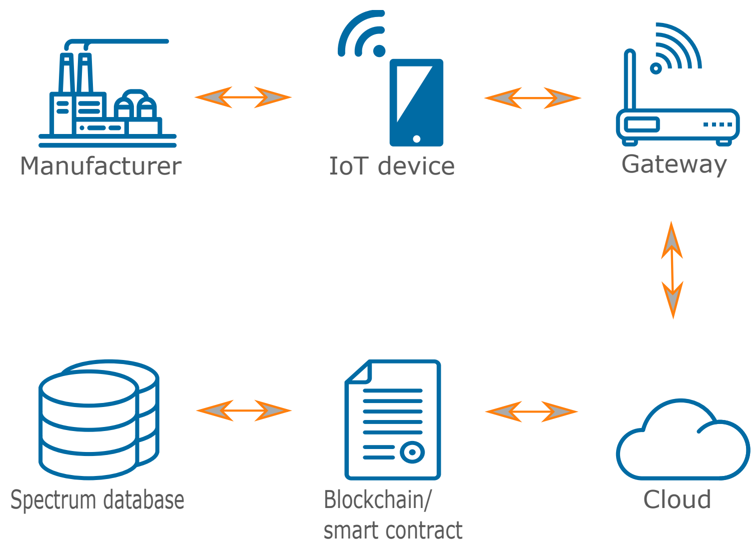

Figure 4.6: System architecture.

and protocols with longer range, more reliability, and higher data rate communications. These advantages are possible, in part, because users of the spectrum can be "managed" for low levels of interference.

4.4.3 The System

The system should fulfill the requirements shown in Table 4.1 and Table 4.2. The requirements express the functions the device and system need to perform, along with the assumptions about the capabilities of the equipment. Communications between the different elements of the system are shown in Fig. 4.6. This section explains the interactions, function, and messages from the time an IoT device turns on until it begins operating. For example purposes, we utilize the private [93] IBM Blockchain platform built on Hyperledger [94]. However, the emphasis is not on the platform, but rather the blockchain concept and the ability to run an IoT smart contract.

(1) An Internet of Things device could be tracked from the time it leaves the factory for security and authentication purposes. For instance, the MAC address, firmware version, and operating system version could be cryptographically hashed. This in-

Table 4.1: System Requirements

System Requirements	
Scalability	Large-scale functionality, compatible with the chosen IoT device(s), can negotiate multiple databases, operates in different countries.
Decentralization	Owned or controlled by multiple entitities.
Heterogeneity	Can support different types of devices, capabilities, and networks.
Flexibility	Able to work under a variety of common protocols and standards due to lack of a unified standard.
Interconnectivity	Able to link with other systems.
Unique Indentity	Identifiable via a unique address.
Authentication	Able to authenticate other devices and be authenticated by them. Able to verify the unique identity and configuration of the device.
Device Authorization	Manage authorizations. Device activity must be authorized.
System/smart contract/ blockchain authorization	Activities must be within the scope of the contract, and the contract must be verified as authentic.
Stakeholder Authorization	Stakeholders must be authenticated, and can only perform activities within their authorized scope.
Security	Storage and processing may limit what can be resident on the device.
Privacy	Able to provide privacy of user information and identity except to authorized stakeholders.
Global	Cross border movement and compliance.
Constraints	Requirements need to be met inexpensively, automatically and at scale.

Table 4.2: Device and Operation Requirements

Device Requirements
Is an IoT device.
Has or connects to sensors (e.g. humidity and temperature for this example).
Is wireless.
Has a policy-based cognitive radio that can change operating characteristics like frequency and power based upon a policy language.
Mobile. Able to function while moving, and in a variety of locations and regulatory regimes.
Able to geolocate (e.g. using GPS).
Able to change operating parameters to meet the current and expected locations.
Independent; not dependent on a master/slave system.
Able to use Internet Protocol v. 6 (IPv6).
System Requirements for Device Operation
Ability to operate with different IoT devices.
Ability to operate in different spectrum bands.
Ability to operate in different locations with different regulatory requirements.

formation can be recorded on a blockchain. When a device is ready to operate it connects to the Internet and contacts a pre-configured blockchain address. The blockchain can verify the hash to confirm the authenticity and starting configuration of the device.

(2) When powered on in its intended location, the device would go online to authenticate/register its manufacturer or global identity and get an identity and credentials on the local network or Internet, such as an IPv6 address. It could update its firmware or configuration and be assigned a new hash for future verification. This process would likely begin in one of the unlicensed industrial, scientific, and medical (ISM) frequencies that are coordinated worldwide. The device could then announce its capabilities and, if known, its needs, to a smart contract running on a blockchain. The IoT device with a smart radio connects to the Internet via IPv6. It then contacts its instance of the blockchain smart contract and provides its location and other necessary information. The smart contract verifies that the information came from an authenticated device and uses the appropriate information as contract inputs.

(3) The IBM Blockchain runs a single smart contract for one shipment of coffee from Rwanda to Italy. However, the contract code is re-usable, with minor modifications, for other shipments. Smart contracts may also be modular, and call other smart contracts. The smart contract takes defined inputs, performs defined functions, and returns outputs. The outputs are operating parameters (the policy directives) for the IoT policy-based cognitive radios. The smart contract will perform other business functions as well, but we focus on spectrum and IoT smart radio operation. Using the modular capabilities of smart contracts, spectrum and radio operations are envisioned as a sub-contract that runs under a master smart contract for the shipment.

(4) The smart contract can only operate for a device that was authenticated via a hash

that matches the one recorded earlier on the blockchain.

(5) The smart contract would contain the "license specification," or the complete set of all possible allowed parameters for IoT device radio operation.

(6) The license specification would be negotiated and agreed by the stakeholders to the smart contract in advance. This process is akin to "writing the code" for the contract.

(7) The IoT device owner and stakeholders such as spectrum managers or regulators would negotiate the contract terms (write the code). This process would require some manual input from the stakeholders to capture intent and verify the intended functions of the contract. This could in fact involve multiple parties and multiple negotiations. For example, the buyer of the coffee can create the initial contract and give other stakeholders permissions that allow them to make specific changes, such as permitting the IoT device manufacturer to make a security update. In the case of the regulator, it is not expected that they would participate directly in contract negotiations; rather, the contract would need to conform to appropriate regulations and interact with the regulatory database. The contract would account, initially, for the spectrum regulations of the country of origin. It would also be configured for the regulations and spectrum databases of the expected transit countries.

(8) The "policy directives," or specific operational parameters for the radio need to be determined and communicated to the radio before operation. The smart contract will not calculate all of the radio operational parameters itself. Rather, it connects to separate (traditional) databases operated by the regulators of the countries it is passing through and uses the parameters provided by those databases as inputs. The blockchain smart contract verifies the authenticity of the radio, gets the location, and knows the radio capabilities. It contacts the appropriate regulatory database and provides information about the location and operating capabilities of the radio.

(9) The smart contract takes outputs from the regulatory database as additional inputs to its contract functions and performs any necessary calculations. Once the policy directives are determined, they are pushed to the IoT policy-based radio. Depending on the requirements of the contract, they may also be recorded on the blockchain or in a separate traditional database. A sample of information recorded upon departure:


```
Block #41607/14/17 6:40 PM
1 Transactions
f557ea90-0b0b-4cef-a492-dd7683f0b001- createAsset
({"asset":{"assetID":"c340c0f81350","CenterFrequency":
600 MHz,"carrier":"Kenya Cargo Ltd.","location":
{"longitude":39.668206,"latitude":-4.043477,"name":
"Mombasa","event":"Departing"}}})
```


(10) The IoT device would get the policy directives from the smart contract, containing all specific policy directives for that device in the current location and operational period. These policy directives could include parameters like the spectrum center frequency, bandwidth location, time or duration of spectrum use, maximum permitted power levels, etc.

(11) The smart radio will receive the operating parameters, configure itself, and begin functioning under the policy directives. A change in location or the passage of time would trigger the process to get new parameters.

(12) In case of a country with no shared spectrum regulations or spectrum database, or no available spectrum, the device will only use the ISM bands. It would be limited to basic functionalities that match the range and throughput available. If unable to send data, it would store it locally until a wireless connection is available.

4.4.4 The Smart Contract

A smart contract is a collection of code and data. A smart contract can call, or even create, another smart contract. On a blockchain, a specific smart contract is available at a unique address. The contract takes a defined set of possible inputs, performs a defined set of functions depending on the inputs, and returns a specific set of outputs. The universe of definite possibilities is based on the combination of inputs and functions and in this case, forms the license specification. The smart contract contains rules and conditions that enable it to make calculations, validate a condition, determine parameters for the IoT device, and request information from the regulatory database when necessary. In the simplest sense, the smart contract is an “If this then that” function. The smart contract database engine is shown in Fig. 4.7.

This example scenario uses one smart contract for one shipment of coffee from Rwanda to Italy. This arrangement mimics a paper-based scenario that uses one contract for one transaction, event, process, or shipment. Other models are, of course, possible. The smart contract would be configured to enable it to contact separate regulatory databases in the countries through which the associated IoT device was expected to travel.

One master smart contract has all involved stakeholders, such the coffee shipper, or the spectrum manager, as parties to the contract. Stakeholders would register for an account, in this case on the IBM Blockchain. The IBM Blockchain hosts the smart contract, shared ledgers, and transactions to or from the blockchain. The IBM Blockchain allows construction of a private blockchain network where stakeholders require an invitation to join. The IBM Blockchain is built on the Linux Foundation’s Hyperledger Project and allows creating a set of rules for a permissioned network that governs what participants can or cannot do. Members control who else can access or join the network. Participants assists in maintenance of the blockchain based upon their permission type [95, 96].

Together, stakeholders would build a smart contract (i.e., negotiate the contract terms)

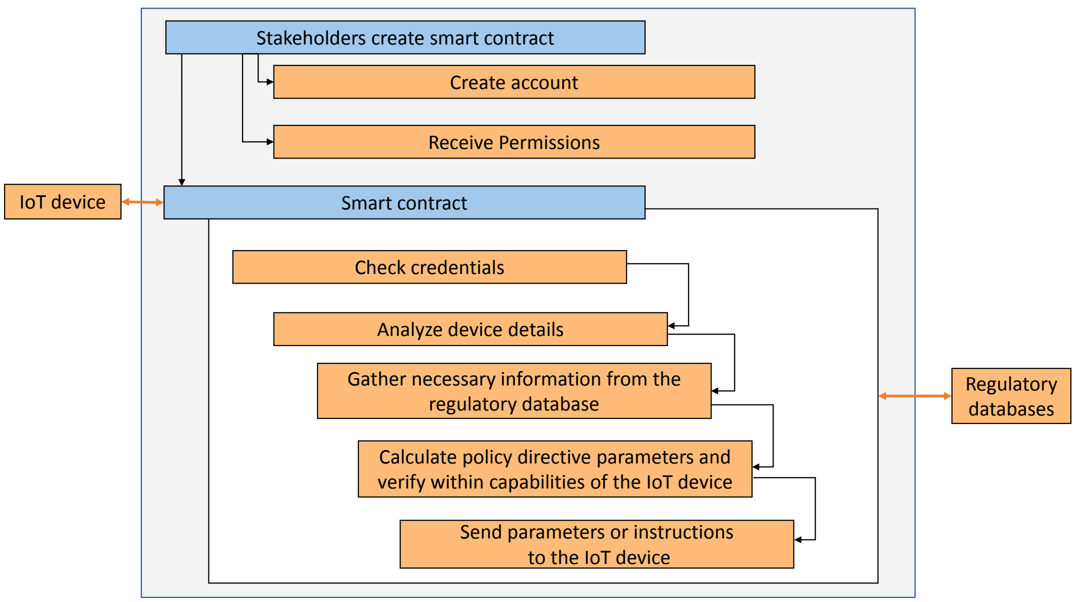

Figure 4.7: The smart contract database engine.

by coding the conditions that will satisfy the "license specification," or the set of all permissible parameters or rules related to configuring the IoT device policy-based radio under the contract. Building the contract includes setting permissions specifying what authority each stakeholder had over each contract parameter. Contract conditions are automatically enforced based upon the code written by the stakeholders.

4.4.5 Connecting and Operating

The messages between the IoT device and the smart contract to enable the previous functions are modeled in Fig. 4.8.

(1) **The IoT Device**

- Device turns on and connects to the Internet.
- Device creates a smart contract discovery message.
- Device receives response from the smart contract.
- Device starts authentication process.
- Device authenticated.
- Device starts the association and configuration process.
- Device sends details like location, radio frequency capability, maximum power output and other parameters to the smart contract.
- Device receives the license specification and configures itself for operation under the parameters.
- Device begins operating.

(2) **Smart Contract on Blockchain**

- Provisions of the smart contract negotiated and written into the contract code.

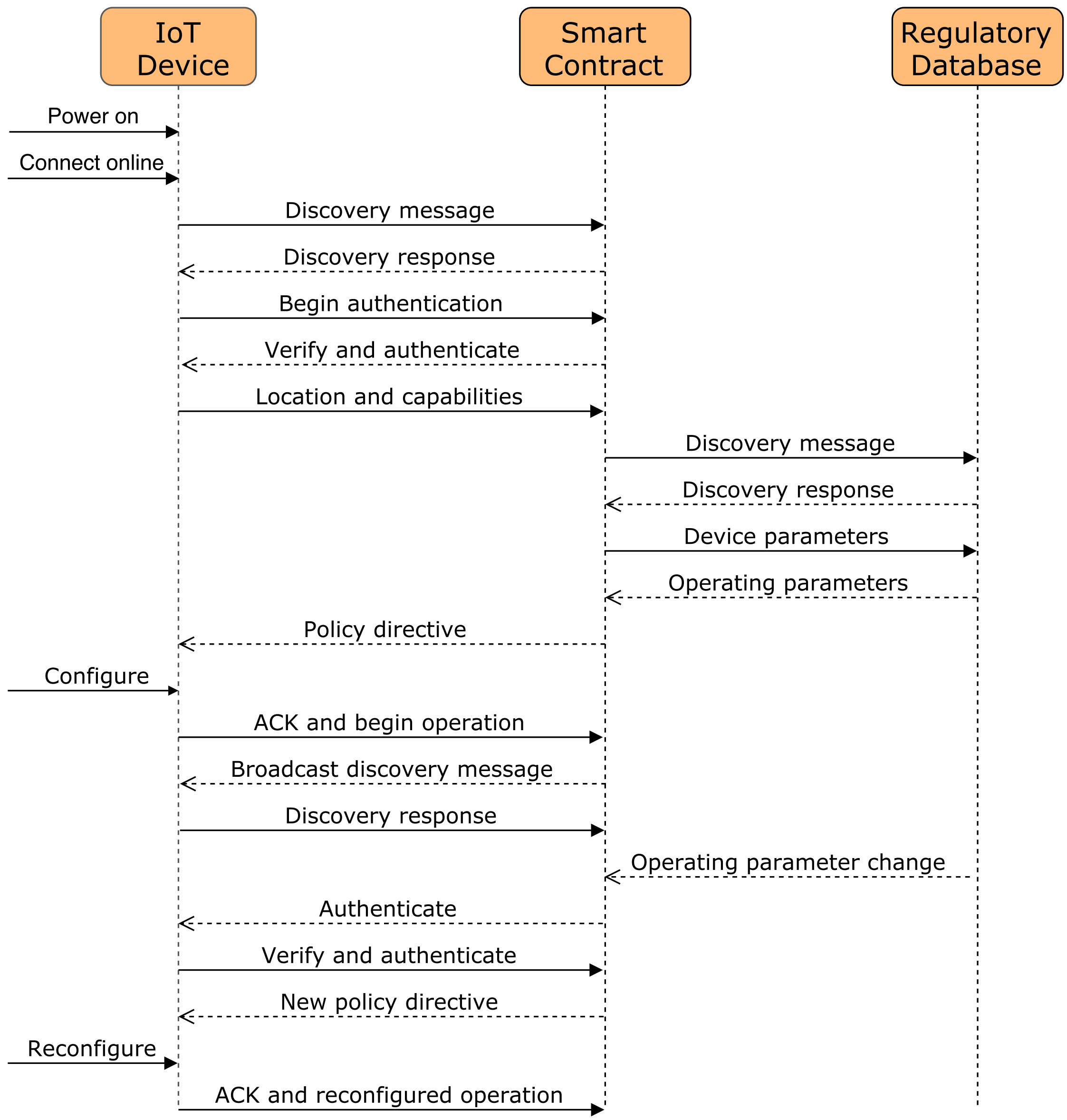

Figure 4.8: Configuration and reconfiguration messages leading to the policy directive.

- The smart contract receives the discovery message from the IoT device.
- The smart contract sends the discovery response to the device.
- The smart contract performs the device authentication process.
- Smart contract receives location and capability inputs from the IoT device.
- The smart contract broadcasts a discovery message for regulatory databases according to the device location.
- The regulatory database responds.
- Device location and relevant parameters are sent to the regulatory database.
- Smart contract receives inputs back from the regulatory database.
- Performs functions to calculate policy directive.
- Checks if device can operate under the parameters of the policy directive, otherwise alternate function/output.
- Pushes policy directive to the IoT device radio and records parameters.
- If the regulatory database notifies the smart contract of an operational change, a defined period of time elapses, or the device moves outside of the allowed operating area, then smart contract will take action to calculate and push a new policy directive to the IoT device.

If stakeholders cannot agree on the policy directives, the device would not begin operation. Similarly, should an unexpected event or input occur, the device would stop transmitting or transition to a state of limited function until the situation is resolved. The dynamic policy license enhances regulatory compliance because devices automatically configure themselves and operate under their policy directives and specifications. Changes are negotiated automatically, and IoT devices are automatically reconfigured when needed.

4.4.6 Prototype

An example of a minimal working application using the IBM Blockchain is given in Appendix B.

This chapter looks to the future of spectrum sharing and spectrum management. The dynamic policy license, while automated in the form of a smart contract, retains the essential features of a license specification and a policy directive. The DPL is adaptable to new situations and new technologies, and can assist in meeting both old and new needs related to spectrum management.

Chapter 5

Conclusion

This thesis begins by asking in what ways could an alternative spectrum licensing model improve spectrum management? We explore this idea through four different chapters, using the first as an introduction of the ideas to follow. The second chapter provides background on the current state of spectrum use and management, including the motivation and importance of searching for better models. In chapter two we also propose the details of the dynamic policy license and illustrate its value via several thought experiments. In the third chapter, we consider the advantages of the license against the well-known Nextel proceedings. These proceedings demonstrate a variety of spectrum management issues that extend beyond the specific facts of the Nextel case. In the fourth chapter, we look forward, encoding a dynamic policy license as a smart contract used to assist with cross-border spectrum coordination of a traveling Internet of Things device. Further synthesizing the specific ideas of these chapters assists in demonstrating that there are situations where the DPL provides a plausible improvement to the current approach to licensing and managing spectrum.

Chapter two reviews common approaches to spectrum property rights and spectrum licensing. Spectrum is fully allocated, mostly using a command-and-control regulatory approach with licenses that leave little future flexibility for regulators once the license is issued. As the current system is frequently slow and inflexible, it creates a condition where spectrum is artificially scarce due to regulatory inefficiencies. Increasingly intensive use of spectrum calls for new means of spectrum sharing and re-use, goals that will be difficult to achieve without a more nimble regulatory framework. To assist with improving spectrum utilization and management, we introduce the idea of the dynamic policy license, including commentary from spectrum experts. The DPL consists of policy directives, which are the operational parameters that may be used by a radio at any given time. The DPL also consists of the license specification, which is the set of all allowed policy directives over the term of the license, along with pre-determined conditions for changing to new policy directives. As the terms of the license specification are determined in advance of issuing the license, the licensee has certainty about the potential scope and timing of parameter changes. The DPL provides assurances to the licensee that spectrum will be available while limiting the possible license parameters to predefined sets. The regulator retains an option to implement some or all of the pre-defined license specification changes in accordance with the terms of the license. This approach provides future flexibility for the regulator and helps to ease the burden of making current decisions about future uncertainty.

The dynamic policy license is not dynamic spectrum access, although they may be complementary. Policy directives may be distributed via policy-based radios and spectrum databases on a push or pull basis, similar to current proposals for dynamic spectrum access. However, notice of proposed policy directive changes may also be delivered by the regulator without the use of an exclusive technology, such as by postal mail. This feature provides for a broader range of potential applications and eases the transition to a new license concept. Via a series of examples, we demonstrate that the dynamic policy license enables the regulator to better manage changes, coexistence, and efficient use of the spectrum. This process is akin to an economic option to make future changes. However, the regulator needs to work closely with potential licensees to ensure that the resulting licenses are not too complicated or too flexible to be of value. We emphasize both that it is the regulator who retains the option to make changes and that the terms of the license still provide certainty and benefits to the licensee. In economic terms, this is possible due to the reduced cost, or friction, of transactions, a condition that results in higher economic and social output for valuable spectrum.

In the third chapter, we use the Nextel proceedings to examine and categorize spectrum management issues. Many of these issues transcend the specific case. We relate these to the preceding chapter as examples of issues where the dynamic policy license could have been helpful.

In addition to categorizing the broader issues, we make the specific argument that giving flexibility to the regulator and certainty to the licensee reduces transaction costs. Doing so reduces economic friction and enables maximizing output and minimizing interference. The regulatory solution to the Nextel problem ultimately was based on rebanding uses to consolidated, compatible frequency bands. The dynamic policy license is particularly well suited to enabling rebanding and could have helped to avoid the long and contentious regulatory proceedings that ultimately unfolded. The dynamic policy license is also a tool to enable secondary spectrum markets without a loss of regulatory control when needed. Had a secondary market existed in the Nextel case, and were public safety allowed to participate, the market would have been able to resolve many of the issues directly. Regulatory intervention would have been available, but a light hand would have been sufficient to achieve similar results to those attained in the actual case.

In the fourth chapter, we propose a future application of the dynamic policy license. We detail the framework for using a blockchain-based smart contract to implement the dynamic policy license and enable cross-border spectrum sharing for the Internet of Things. Looking forward anticipates the growth of several current trends, including a time when spectrum sharing and re-use may become the norm, with regulatory databases having a role in coordinating spectrum use. The Internet of Things will continue to develop, along with complementary applications of the blockchain. Device mobility will be widespread, and there will be a need to coordinate dynamic spectrum use internationally.

Future work on the dynamic policy license concept could include more engagement with regulators, both in the US and internationally, to move the idea toward implementation.

In the US, this could include drafting a Notice of Inquiry-style document that solicits or incorporates input from sector stakeholders such as industry, equipment manufacturers, or government spectrum users. From a policy analysis perspective, it may be possible to build a cost-benefit model that attempts to quantify the economic impact of the dynamic policy license in different applications. For instance, if it is anticipated that spectrum could fetch less revenue in an auction if the regulator retains options, a policy analysis that attempts to quantify this reduction could be useful.

The dynamic policy license supports a variety of spectrum management functions, regardless of the licensing philosophy, or the way license is assigned. To keep pace with rapid changes in technology, demand, and use, make efficient use of the spectrum over time, and assist in managing coexistence, more dynamic and flexible license and management processes are needed. The accelerating pace of technology and more intensive use of spectrum requires nimble regulatory foundations to respond to rapidly evolving conditions in the market. The dynamic policy license is one way to provide flexibility under the control of the regulator and certainty for the licensee.

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Appendix A

Probability of Getting a License

This appendix analyzes the probability of getting a license for fixed and flexible licensees as described in Section 2.3.3. Assume each license corresponds to a fixed transmitter. A license is assigned if the potential license has 0 or 1 neighbors within distance R, and if it has 2 neighbors in a non-conflicting configuration. Let this non-conflicting configuration occur a fraction f of the time. Though it is possible, we ignore the case of 3 or more neighbors since the probability of a non-conflicting configuration is negligible.

Assume the licensees are distributed randomly according to a two-dimensional Poisson process. According to Poisson theory, if we pick a "typical" licensee and draw a circle of radius R around their location, then, the license is assigned with probability:

$$P_{\mathrm{la}} = e^{-x}\left(1 + x + \frac{f}{2}x^2\right)$$

where $x = \lambda \pi R^2 \frac{2}{N}$, $\frac{N}{2}$ is the number of frequency groups, and λ is the license density. For a given f and P_{la}, x can be solved for numerically.

The difference between the two scenarios is f, the probability that a node with two neighbors can find an assignment. In the flexible situation, this occurs whenever the two neighbors are not themselves neighbors, which numerical integration shows to be $f = 41.4\%$ of the instances. In the fixed case, half of these instances will have two neighbors with different channels assigned, and no assignment is found, and so $f = 20.7\%$.

We solve numerically for x_{fix} and x_{flex} as a function of P_{la} and compute $x_{\mathrm{flex}}/x_{\mathrm{fix}} = \lambda_{\mathrm{flex}}/\lambda_{\mathrm{fix}}$, the gain in density shown in Table 2.3.

Appendix B

A Smart Contract Prototype for Cross-Border Spectrum Access

In this appendix we develop a prototype smart contract application in support of the coffee trading example. As there is no regulator database or agile radio IoT device, we simulate these inputs and outputs. We also simplify the example to only a subset of the journey and possible parameters. When the IoT device leaves Kigali, Rwanda and reaches the Kenya border, it asks the simulated regulator database for a new center frequency, bandwidth, and authorized time period. We simulate the Kenya border as a simple latitude/longitude point. If no spectrum is available, the device ceases to transmit in the old authorized frequency. At this point it would need to fall back on another authorization channel, such as WiFi or LoRa in the ISM bands.

B.1 The IBM Blockchain

The prototype was developed using the IBM Blockchain development environment. The IBM Blockchain is based on the Hyperledger Project from the Linux Foundation, and includes a development framework called Hyperledger Composer [96]. The IBM Blockchain is a private, permissioned network where all participating entities are known [96]. Each user runs a Hyperledger instance and keeps a copy of the ledger. Because all users are known, transactions are not verified through the process of mining as in the well-known Bitcoin blockchain. Instead, Hyperledger uses the Practical Byzantine Fault Tolerance (PBFT) algorithm [97] to maintain consensus as to the state of the transaction ledger between all users on the network [98].

Hyperledger Composer was used to create a model business network with assets, transactions, events and participants. Transaction functions were created that define the conditions under which a transaction occurs. Query definitions are used to extract data from the business network. Access control lists contain the permissions and rules that govern access to the application and permissions [99].

B.2 Building the Network

In this working example, we show a scenario between two stakeholders, a coffee factory in Italy serving as the buyer, and a seller in Rwanda. In this example, the contract is created by the buyer. An IoT device with sensors and an agile radio is attached to the coffee shipment throughout the journey across several borders. The device location is tracked, and events trigger transactions between the IoT device and the smart contract. Events such as the crossing of a border trigger requests for an update of the allowed radio operating parameters, including the center frequency, bandwidth, and duration of the channel allocation.

A business network is defined with five components [100]:

Assets can be goods, property or services. They must have a unique ID, and can contain properties defined by the application developer. Assets can have a relationship with other assets or other participants. In this example we define two assets: A `Sensor` for the parameters to be used by the sensor and `Spectrum` to simulate the data in the regulatory database.

Transactions are the processes through which participants interact with assets. They define the allowed actions, such as trading goods or buying a house. They are the interactions that affect the state of assets on the blockchain ledger. Transactions are defined by inputs and transaction processor scripts. In the example we create a transaction to update the parameters of the IoT device radio. When the device reaches a certain location (border crossing), the smart contract is notified of the location update and triggers a transaction processor script that requests new operating parameters for that location.

Participants are the members of the business network that interact with the asset. They are associated with a unique ID and can be used across multiple business networks. They can own assets and submit transactions within the scope of their authorization. In this example there are only two participants, a `Buyer` and a `Seller`. Participants and their permissions are set by the creator of the contract, in this case, the buyer.

Events are defined in the business network model, and are later "emitted." They are part of the transaction processor script and are emitted as outputs by the script. When an event is emitted, it is to show an external system that something significant was recorded in the ledger. In our example, two events will be emitted, an `UpdateSpectrumParametersEvent` and a `StopTransmittingEvent`. The first event shows an update of the shipment location. The second event is emitted when there is no available spectrum in the new location and the contract sends a message to the sensor to stop transmitting. In general, events take a certain condition, or state change of the transaction, and send a defined output to an external system.

Concepts are constructs that do not fit the definition of an asset, participant, transaction, or event. In our example network, the location or address is modeled as a concept.

B.3 Defining the Network

In the IBM Blockchain framework, the first step is to create a *business network*. For this example, a business network named `iotblockchain` was created. IBMs Blockchain framework provides each participant with a "wallet" that contains a "business card." The business card represents the identity of the participant with an enrollment ID and a secret key. The business card is used to connect to the business network.

After creating the business network, the coffee buyer creates a *namespace* for the project, where all resource definitions are stored.

```
namespace org.acme.mynetwork
```

Next, the location concept is created.

```
concept Address {
  o String city optional
  o String country
  o String street optional
}
```

Then the coffee buyer creates the Assets `Sensor` and `Spectrum`. These will contain the simulated parameters for the two assets.

```
/**
 * Sensor asset
 */
asset Sensor identified by assetID {
    o String assetID
    o String centerfrequency
    o String bandwidth
    o String duration
    o String longitude
    o String latitude
    o String LocationName
    o ShipmentStatus shipmentStatus
}

/**
 * Spectrum asset
 */
```

```
asset Spectrum identified by SpectrumId {
    o String SpectrumId
    o String centerfrequency
    o String bandwidth
    o String duration
    o String CorrespondingLocation
}
```

The next step is to create the Participants `Buyer` and `Seller`.

```
/**
 * An abstract participant type in this business network
 */
abstract participant Business identified by email {
  o String email
  o Address address
}

/**
 * A Buyer is a type of participant in the network
 */
participant Buyer extends Business {
}

/**
 * A Seller is a type of participant in the network
 */
participant Seller extends Business {
```

```
}
```

Next, the buyer creates the Events `UpdateSpectrumParametersEvent` and `StopTransmittingEvent`. These are notifications generated by the smart contract and consumed or used by an external entity, in this case, the IoT device radio. The `StopTransmittingEvent` is emitted if there is no spectrum available, and the `UpdateSpectrumParametersEvent` is emitted when the device crosses a defined point simulating a border crossing.

```
/**
 * Event when there a change in the spectrum parameters due to a new location
 */
event UpdateSpectrumParametersEvent {
}


/**
 * Event when there is no available spectrum
 */
event StopTransmittingEvent {
}
```

Next, the buyer models the Transaction `UpdateSpectrumParameters`, used to pass new parameters to an IoT device radio based on reaching a defined location.

```
/**
 * A transaction to update the device parameters
 */
transaction UpdateSpectrumParameters {
    --> Sensor sensor
    o String newlongitude
```

```
    o String newlatitude
}
```

Next, a query is created to available spectrum parameters from the regulatory database.

```
query spectrumSave {
    description: "Select all drivers aged older than PARAM"
    statement:
        SELECT org.acme.mynetwork.Spectrum
            WHERE (CorrespondingLocation == _$locationName)
}
```

Next a transaction processor script named `Spectrumupdate` is created. This function is used to transmit spectrum availability details from the smart contract to the IoT device radio. This script defines the actions taken when the IoT device reaches a defined point, representing a country border. Actions include querying the spectrum database for new parameters, passing the parameters to the IoT device radio, and emitting appropriate events to record the new spectrum parameters or stop transmitting if no spectrum is available.

```
/**
 * This transaction is used to update the Iot device radio with the
 * spectrum it can use in a defined location.
 * @param {org.acme.mynetwork.UpdateSpectrumParameters}
 * updateSpectrumParameters - the spectrum to be processed
 */
function Spectrumupdate(updateSpectrumParameters) {

/**
 * Check previous location
 */
```

```
    var oldlongitude = updateSpectrumParameters.sensor.longitude;
          var oldlatitude = updateSpectrumParameters.sensor.latitude;
          var factory = getFactory();

/**
 * Update if new location
 */
  if (oldlongitude != updateSpectrumParameters.newlongitude &&
  oldlatitude != updateSpectrumParameters.newlatitude){

/**
 * Traveling from Rwanda to Kenya, if this latitude and longitude is reached
 * (representing approx. 10 km before the Kenya border), contact the Kenya
 * regulatory database and get and store spectrum parameters to use when the
 * border is reached.
 */
    if (updateSpectrumParameters.newlongitude == "36.7820" &&
    updateSpectrumParameters.newlatitude == "-2.5552"){
            return getAssetRegistry('org.acme.mynetwork.Spectrum')
            .then(function (assetRegistry) {
                    return query('spectrumSave', {locationName : 'Kenya'})
                            .then(function (results) {
               spectrumcenterfrequency = results[0].centerfrequency;
        spectrumbandwidth = results[0].bandwidth;
        spectrumduration  = results[0].duration;
        console.log('**** MESSAGE ' + results[0].getIdentifier() +
        ' bandwidth is ' + spectrumbandwidth + ' on a center frequency of '
```

```
        + spectrumcenterfrequency + ' for ' + spectrumduration);
/**
 * updateSpectrumParameters.sensor.sprange = spectrumValue;
 */
  });
 });
}

/**
 * Traveling from Kenya to Italy, if this latitude and longitude is reached
 * (representing approx. 10 km before the Italy border), contact the Italy
 * regulatory database and get and store spectrum parameters to use when the
 * border is reached.
 */
    if (updateSpectrumParameters.newlongitude == "13.6786" &&
    updateSpectrumParameters.newlatitude == "45.6168"){
            return getAssetRegistry('org.acme.mynetwork.Spectrum')
            .then(function (assetRegistry) {
                    return query('spectrumSave', {locationName : 'Italy'})
                            .then(function (results) {
                spectrumcenterfrequency = results[0].centerfrequency;
        spectrumbandwidth = results[0].bandwidth;
        spectrumduration  = results[0].duration;

console.log('**** MESSAGE ' + results[0].getIdentifier() + ' bandwidth is '
+ spectrumbandwidth + ' on a center frequency of ' + spectrumcenterfrequency
+ ' for ' + spectrumduration);
```

```
  });
 });
}

/**
 * Upon reaching the border the new spectrum parameters are passed to the
 * device
 */
    if (updateSpectrumParameters.newlongitude == "30.1044" &&
    updateSpectrumParameters.newlatitude == "1.9706"){

/*
* Get the sensor's location, then look for the corresponding saved
* informations for new spectrum parameters.
*/
                updateSpectrumParameters.sensor.longitude =
                updateSpectrumParameters.newlongitude;
                updateSpectrumParameters.sensor.latitude =
                updateSpectrumParameters.newlatitude;

/**
 * query the temporary database
 */

    return getAssetRegistry('org.acme.mynetwork.Sensor')
        .then(function (assetRegistry) {
                    return query('spectrumSave',
```

```
                        {locationName : 'Rwanda'})
                            .then(function (results) {
                 updateSpectrumParameters.sensor.centerfrequency =
                 results[0].centerfrequency;
                 updateSpectrumParameters.sensor.bandwidth =
                 results[0].bandwidth;
                 updateSpectrumParameters.sensor.duration =
                 results[0].duration;
                 updateSpectrumParameters.sensor.LocationName =
                 results[0].CorrespondingLocation;

/**
 * If there is no spectrum available send a message to the device to stop
 * transmitting
 */

        if (updateSpectrumParameters.sensor.centerfrequency != "" &&
        updateSpectrumParameters.sensor.bandwidth != "" &&
        updateSpectrumParameters.sensor.duration != ""){
               return assetRegistry.update(updateSpectrumParameters.sensor);
               }
               else{

 var StopTransmitting = factory.newEvent('org.acme.mynetwork',
 'StopTransmittingEvent');
                console.log('** No spectrum available, stopping ** ');
                    emit(StopTransmitting);
```

```
    }
   });
  });
 }

/**
 * For location Mombasa
 */

    else if (updateSpectrumParameters.newlongitude == "39.6682" &&
    updateSpectrumParameters.newlatitude == "4.0435"){
      updateSpectrumParameters.sensor.longitude =
      updateSpectrumParameters.newlongitude;
      updateSpectrumParameters.sensor.latitude =
      updateSpectrumParameters.newlatitude;

/**
 * query the temporary database
 */

    return getAssetRegistry('org.acme.mynetwork.Sensor')
        .then(function (assetRegistry) {
                    return query('spectrumSave',
                    {locationName : 'Kenya'})
                        .then(function (results) {

         updateSpectrumParameters.sensor.centerfrequency =
```

```
          results[0].centerfrequency;
          updateSpectrumParameters.sensor.bandwidth =
          results[0].bandwidth;
          updateSpectrumParameters.sensor.duration =
          results[0].duration;
            updateSpectrumParameters.sensor.LocationName =
      results[0].CorrespondingLocation;

/**
 * If there is no spectrum available send a message to the device to stop
 * transmitting
 */
         if (updateSpectrumParameters.sensor.centerfrequency != "" &&
         updateSpectrumParameters.sensor.bandwidth != "" &&
         updateSpectrumParameters.sensor.duration != ""){

var updateParameter = factory.newEvent('org.acme.mynetwork',
'UpdateSpectrumParametersEvent');
      console.log('** The spectrum parameters are updated **');
          emit(updateParameter)
            return assetRegistry.update(updateSpectrumParameters.sensor);}
            else{

var StopTransmitting =
factory.newEvent('org.acme.mynetwork','StopTransmittingEvent');
                console.log('** No spectrum available, stopping ** ');
                    emit(StopTransmitting);
```

```
   }
  });
 });
}

/**
 * For location Trieste
 */

    else if (updateSpectrumParameters.newlongitude == "13.7768" &&
    updateSpectrumParameters.newlatitude == "45.6495"){
      updateSpectrumParameters.sensor.longitude =
      updateSpectrumParameters.newlongitude;
      updateSpectrumParameters.sensor.latitude =
      updateSpectrumParameters.newlatitude;

/**
 * query the temporary database
 */

    return getAssetRegistry('org.acme.mynetwork.Sensor')
        .then(function (assetRegistry) {
            return query('spectrumSave', {locationName : 'Italy'})
                            .then(function (results) {

updateSpectrumParameters.sensor.centerfrequency =
results[0].centerfrequency;
```

```
updateSpectrumParameters.sensor.bandwidth = results[0].bandwidth;
updateSpectrumParameters.sensor.duration = results[0].duration;
updateSpectrumParameters.sensor.LocationName =
results[0].CorrespondingLocation;

/**
 * If there is no spectrum available send a message to the sensor to stop
 * transmitting
 */
           if (updateSpectrumParameters.sensor.centerfrequency != "" &&
                   updateSpectrumParameters.sensor.bandwidth != "" &&
                   updateSpectrumParameters.sensor.duration != ""){
           return assetRegistry.update(updateSpectrumParameters.sensor);}
           else{

     var StopTransmitting = factory.newEvent('org.acme.mynetwork',
     'StopTransmittingEvent');
        console.log('** No spectrum available, stopping **');
                    emit(StopTransmitting);
     }
    });
   });
  }
 }
}
```

The buyer defines the access control rules and deploys the new business network. For the prototype, all participants are allowed access to all resources, but different permission levels are possible.

```
/**
 * Access control rules for mynetwork
 */
rule Default {
    description: "Allow all participants access to all resources"
    participant: "ANY"
    operation: ALL
    resource: "org.acme.mynetwork.*"
    action: ALLOW
}

rule SystemACL {
  description:  "System ACL to permit all access"
  participant: "ANY"
  operation: ALL
  resource: "org.hyperledger.composer.system.**"
  action: ALLOW
}
```

B.4 Deploying and Running

The buyer can create participants (with their addresses and emails), assets (IoT devices) and transactions (updating the device information by location). If the device reaches the Kenyan border, this information is communicated to the smart contract, and the contract obtains and passes the correct parameters to the IoT device radio. The smart contract calls the `UpdateSpectrumParameters` transaction, which is processed by the `Spectrumupdate` function.

The device provides its identification and location. After receiving this information, the function will check the corresponding location, query the database, `spectrumSave` the corresponding location spectrum parameters, and send them to the IoT device radio.

Before the Shipment leaves Kigali, the buyer will create the smart contract and include the members.

The buyer:


```
{
  "$class": "org.acme.mynetwork.Buyer",
  "email": "buyer@gmail.com",
  "address": {
    "$class": "org.acme.mynetwork.Address",
    "city": "Trieste",
    "country": "Italy"
  }
}
```


The seller:


```
{
  "$class": "org.acme.mynetwork.seller",
  "email": "seller@gmail.com",
  "address": {
    "$class": "org.acme.mynetwork.Address",
    "city": "",
    "country": ""
  }
```

```
}
```

The buyer also connects the appropriate assets. In the prototype these are simulations of the regulatory database (the spectrum asset) and IoT device. The simulated regulatory database assets:

For Rwanda:


```
{
  "$class": "org.acme.mynetwork.Spectrum",
  "SpectrumId": "sp1",
  "centerfrequency": "600 MHz",
  "bandwidth": "20 kHz",
  "duration": "72 hours",
  "CorrespondingLocation": "Rwanda"
}
```


For Kenya:


```
{
  "$class": "org.acme.mynetwork.Spectrum",
  "SpectrumId": "sp2",
  "centerfrequency": "650 MHz",
  "bandwidth": "20 kHz",
  "duration": "24 h",
  "CorrespondingLocation": "Kenya"
}
```


For Italy:


```
{
  "$class": "org.acme.mynetwork.Spectrum",
```

```
  "SpectrumId": "sp3",
  "centerfrequency": "620 MHz",
  "bandwidth": "20 kHz",
  "duration": "24 h",
  "CorrespondingLocation": "Italy"
}
```


For the simulated IoT device:


```
{
  "$class": "org.acme.mynetwork.Sensor",
  "assetID": "sensor1",
  "centerfrequency": "",
  "bandwidth": "",
  "duration": "",
  "longitude": "",
  "latitude": "",
  "LocationName": ""
}
```


When the coffee shipment reaches Kigali, the IoT device sends the following input to the smart contract:


```
{
  "$class": "org.acme.mynetwork.UpdateSpectrumParameters",
  "sensor": "resource:org.acme.mynetwork.Sensor#s1",
  "newlongitude": "30.1044",
  "newlatitude": "1.9706"
}
```

The IoT device radio receives the appropriate spectrum parameters for that location. Simultaneously, the `UpdateSpectrumParametersEvent` is emitted (via the `Spectrumupdate` function). The IoT device then has the new spectrum values:


```
{
  "$class": "org.acme.mynetwork.Sensor",
  "assetID": "s1",
  "centerfrequency": "400 MHz",
  "bandwidth": "20 KHz",
  "duration": "72 hours",
  "longitude": "30.1044",
  "latitude": "1.9706",
  "LocationName": "Rwanda"
}
```


And the ledger is updated:


```
{
 "$class": "org.acme.mynetwork.UpdateSpectrumParameters",
 "sensor": "resource:org.acme.mynetwork.Sensor#s1",
 "newlongitude": "30.1044",
 "newlatitude": "1.9706",
 "transactionId": "d019670a-7c9b-40a1-b113-fe1fe90a6336",
 "timestamp": "2017-11-18T09:17:19.338Z"
}
```


Before it crosses the Kenya border, the IoT device sends it location to the smart contract, which the queries the simulated regulatory database (Spectrum asset) to get the appropriate parameters. The parameters received can be seen in the console as the spectrum ID, the center frequency and the duration for that location:

```
**** MESSAGE sp2 bandwidth is 20 Khz on a center frequency of 600 MHz
for 24 h
```

After it crosses the Kenya border traveling to Mombasa, the IoT device sends input to the smart contract:


```
{
  "$class": "org.acme.mynetwork.UpdateSpectrumParameters",
  "sensor": "resource:org.acme.mynetwork.Sensor#s1",
  "newlongitude": "39.6682",
  "newlatitude": "4.0435"
}
```


The IoT device receives the spectrum parameters to use in that location. Simultaneously, the `UpdateSpectrumParametersEvent` is emitted (via the `Spectrumupdate` function). The IoT device then has the new spectrum values:


```
{
  "$class": "org.acme.mynetwork.Sensor",
  "assetID": "s1",
  "centerfrequency": "600 MHz",
  "bandwidth": "20 Khz",
  "duration": "24 h",
  "longitude": "39.6682",
  "latitude": "4.0435",
  "LocationName": "Kenya"
}
```


The event update is emitted:


```
{
 "$class": "org.acme.mynetwork.UpdateSpectrumParametersEvent",
```

```
 "eventId": "b937fd70-1f8d-4482-9fb9-2f92bbda8f4a#0",
 "timestamp": "2017-11-17T09:31:35.323Z"
}
```


And the ledger is updated:


```
{
 "$class": "org.acme.mynetwork.UpdateSpectrumParameters",
 "sensor": "resource:org.acme.mynetwork.Sensor#s1",
 "newlongitude": "39.6682",
 "newlatitude": "4.0435",
 "transactionId": "b937fd70-1f8d-4482-9fb9-2f92bbda8f4a",
 "timestamp": "2017-11-17T09:31:35.323Z"
}
```