Cognitive radio
the key to a new radio spectrum paradigm

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Master of Science
in Innovation Sciences
**List of Abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AM</td>
<td>Amplitude Modulation</td>
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<tr>
<td>BSC</td>
<td>Base Station Controller</td>
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<tr>
<td>BTS</td>
<td>Base Transceiver Station</td>
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<tr>
<td>CEPT</td>
<td>Conférence européenne des administrations des postes et télécommunications</td>
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<tr>
<td>CLEC</td>
<td>Competing Local Exchange Carrier</td>
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<td>CPR</td>
<td>Common-Pool Resource</td>
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<td>CR</td>
<td>Cognitive Radio</td>
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<tr>
<td>CUS</td>
<td>Collective Use of Spectrum</td>
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<td>DAE</td>
<td>Digital Agenda Europe</td>
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<td>DCFA</td>
<td>Device Controlled Frequency Access</td>
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<tr>
<td>EC</td>
<td>European Commission</td>
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<tr>
<td>ECC</td>
<td>Electronic Communications Committee</td>
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<td>EEC</td>
<td>European Economic Community</td>
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<td>ETSI</td>
<td>European Telecommunications Standards Institute</td>
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<td>EU</td>
<td>European Union</td>
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<tr>
<td>FDD</td>
<td>Frequency Division Duplexing</td>
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<td>FM</td>
<td>Frequency Modulation</td>
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<tr>
<td>GPRS</td>
<td>General Packet Radio Service</td>
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<tr>
<td>GSMA</td>
<td>Groupe Spécial Mobile Association</td>
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<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
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<tr>
<td>IMSI</td>
<td>International Mobile Subscriber Identity</td>
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<tr>
<td>ISM</td>
<td>Industrial Scientific and Medial</td>
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<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
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<tr>
<td>ITU</td>
<td>International Telecommunications Union</td>
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<tr>
<td>LAN</td>
<td>Local Area Network</td>
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<tr>
<td>LEC</td>
<td>Local Exchange Carrier</td>
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<tr>
<td>LLU</td>
<td>Local Loop Unbundling</td>
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<td>LSA</td>
<td>Licensed Spectrum Access</td>
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<tr>
<td>LTE</td>
<td>Long Term Evolution</td>
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<tr>
<td>ME</td>
<td>Mobile Equipment</td>
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<tr>
<td>MNO</td>
<td>Mobile Network Operator</td>
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<tr>
<td>MSC</td>
<td>Mobile Switching Center</td>
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<td>NMT</td>
<td>Nordic Mobile Telephone</td>
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<tr>
<td>NRA</td>
<td>National Regulatory Authority</td>
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<td>PMC</td>
<td>Personal Mobile Communication</td>
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<tr>
<td>PSTN</td>
<td>Public Switched Telephone Network</td>
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<td>RSPG</td>
<td>Radio Spectrum Policy Group</td>
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<td>RSPP</td>
<td>Radio Spectrum Policy Programme</td>
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<td>SDR</td>
<td>Software Defined Radio</td>
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<tr>
<td>TDD</td>
<td>Time Division Duplexing</td>
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<tr>
<td>UHF</td>
<td>Ultra-High Frequency</td>
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<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunications System</td>
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<td>WRC</td>
<td>World Radio Conference</td>
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Executive Summary

Introduction
Virtually everyone uses a mobile phone for communicating. They are vital to our everyday lives and a great enabler of many different economic activities. Mobile phones, service providers and the services that they enable are collectively called Personal Mobile Communications (PMC). Their wireless transmissions use a part of the electromagnetic spectrum called the radio spectrum, often referred to as spectrum for short. There have been signs lately that there will be problems in the near future for PMC and other wireless transmissions. The number of users of PMC services has increased tremendously over the last decade and will continue to do so in the near future. At the same time, more and more other applications are starting to use wireless transmissions like for instance the Internet of things. This will lead to spectrum shortages in the near future. Spectrum is a special type of common-pool resource (CPR): it’s non-excludable, but rivalrous in nature. There have been plans to deal with the problem including the addition of more spectrum bands to PMC. This paper examines a new family of technologies called Cognitive Radio (CR): a radio system that can self-configure its parameters and get better at doing this over time. The goal of this paper is to determine if CR can enable a new paradigm in the field of PMC. It will do this by examining research about the state of CR technologies and CPR resource management. It’ll look at the current state of rules and regulations surrounding PMC, and finally define a new paradigm for spectrum management in the PMC space. The main research question is:

Can cognitive radio technologies enable a new paradigm of spectrum management in the field of personal mobile communication?

This research question is extensive so it’ll be divided into multiple parts:

1) How can cognitive radio contribute to meeting future requirements in mobile communications?

2) What does a new framework for implementing cognitive radio look like? (i.e. what needs to change in the current paradigm of mobile communications?).

3) Will radio spectrum be properly managed by this new paradigm?

Cognitive radio
PMC systems span the world, and have been standardized by various standards bodies. Radio spectrum has a limitation as to how much information can be transferred in a given frequency band. This is partly because of interference: if two transmissions are carried out on the same frequency, at the same time, in the same area, they will interfere each other. All sorts of different applications of wireless transmissions operate on different static spectrum bands. Cognitive technology changes this. The system is based on software-defined radio, which can change parameters like central frequency, bandwidth and transmission power. It can do this quickly by using software instead of specialized circuits. Cognitive radio adds to that capability by learning over time what the best parameters are given a certain set of circumstances. It can sense other transmissions and their parameter using a process called spectrum sensing. The system can then alter its transmission parameters based on that information. CR systems can become the underpinnings for a new generation of PMC and can
allow for more and new applications in the PMC spectrum. It can enable spectrum sharing: the cooperative sharing of spectrum where many different parties use the same pool of radio spectrum and let the CR technology deal with the interference automatically. It can also save on operational cost, it can be reconfigured more easily and its learning capabilities will amplify these benefits.

**Governing spectrum**
When radio applications where first being developed there weren’t any rules and regulations that limited their access. Eventually, the command and control system was developed: governments would assign the radio spectrum in name of the people. As a part of that assignment, certain bands could be licensed for certain applications. One of these applications was PMC, and to license a band a want-to-be mobile network operator (MNO) would have to participate in a spectrum auction. They would obtain exclusive access to the spectrum for a given period of time. This system was set up to deal with interference given today’s technology. It does provide inefficient results, as the different bands need gaps in between them called whitespaces to prevent interference between different MNOs. It also gives them relatively much control over the spectrum as they have exclusive access rights for a certain period of time. There are alternative approaches such as the market approach: allow people to buy and trade spectrum, and the commons approach: allow everyone access to a big pool of radio spectrum. The EU wants change current spectrum policies. Their goals include adding more spectrum for PMC applications, allow license holders to trade their licenses, and allow secondary parties to access unused licensed spectrum. They haven’t shown any intention to move away from the general command and control system.

**Common-pool resources**
Radio spectrum is a special kind of natural resource and it’s a unique common-pool resource. Common-pool resources are non-excludable but rivalrous resources. It’s hard to exclude anyone from using or consuming them, but if one person uses a portion of it, another person can’t anymore. Radio spectrum is unique because it is locally and temporally scarce. Once a transmission stops the spectrum is instantly useable again. When left without restriction, CPRs are part of the commons. The commons are all natural and cultural resources that are accessible to all members of a society. Natural resources belonging to the commons often fall prey to the tragedy of the commons. This is because people don’t experience a direct negative impact from marginally increasing their consumption. Eventually, enough people do this and the resource is depleted, leaving everyone without it. Rules and regulations are almost always needed to manage a CPR properly, as is the case with radio spectrum. These rules and regulations are based on current technologies, and aren’t suitable to facilitate the benefits that CR technologies can bring. Property rights are often the start of CPR management: in the case of spectrum they are held by the government. Some management rights and usage rights are given to the MNOs and the users respectively. Ostrom (1990) has set up a framework for CPR management that is made up of a number of design principles. These will be used to test the new framework to determine if it deals with radio spectrum as a CPR properly.

**Device Controlled Frequency Access**
The new paradigm is called Device Controlled Frequency Access (DCFA). It removes the spectrum licenses and instead takes all the currently licensed spectrum and puts it into one spectrum pool. Each MNO can offer access using that big pool, and base stations and phones will be outfitted with CR capabilities. A base-station will be able to change the parameters of the transmissions based on spectrum sensing information from the phones. The PMC spectrum pool can potentially include parts of the open spectrum as well, as CR technologies can alter their transmission parameters if necessary. Users will thus get more freedom to use...
short-range transmissions in the big PMC pool, which can lead to new applications and
innovation. The way you pay for PMC access will also change: instead of have to buy a two-
year contract, users change between different MNOs based on price and quality of service.
MNOs can offer their best prices via a real-time auction to the user. These can happen in a
time span of 100 milliseconds, and can be held if users move to a new geographical area or
other parameters change. A software layer called the Intermediate will facilitate these
auctions and bill the users. It can then transfer the money to the MNOs based on the amount
of data transmissions they’ve facilitated. The new paradigm is tested using Ostrom’s design
principles, and it is found to be a better way to manage spectrum from a CPR point of view.
It’s also provides more social value that the current paradigm.

Conclusion
The research question has been answered: DCFA is a new paradigm that is made possible
because of CR-based technologies. There are some limitations to this research, which is
mainly because of uncertainties about the capabilities of the technology. A lot of real world
testing is necessary to eliminate the uncertainties. The following recommendations are set
based on the outcome of this research.

- Governments and the European commission must discuss the implementation of
DCFA and move to put legislation in place to make this possible. They should
investigate the legal implications of DCFA. There is a lot of legislation
surrounding PMC and MNOs, which will have to change in order for DCFA to be
implemented.
- Governments must also work together closely with private parties like MNOs,
infrastructure manufactures and mobile equipment manufactures and direct
them to producing CR based equipment. There should be testing as soon as
possible to validate the possibility of a CR based PMC network. This must include
both the technical side and the payment side of DCFA.
- Tests must also show how much more efficiently the spectrum is used, and they
must show the extent to which new short-range applications can be developed in
the PMC spectrum pool. This incentive parties to move to DCFA.
- Governments and the EU must push CR technologies along with the new DCFA
framework with the standards bodies.
- MNOs should investigate what steps are necessary to transfer their infrastructure
over to DCFA.
- MNOs and governments should also test and investigate the implementation
details of the real-time biddings.
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1: Introduction

1.1: Research Subject

1.1.1: Communication

Humans are social beings and spend a lot of time communicating with each other. Communication can be defined as the imparting or exchanging of information by speaking, writing, or some other medium. For the vast majority of human history, this was limited to face-to-face communication and writing. The 20th century brought other mediums that enabled more forms of communication: technologies like the telegraph, the telephone, the radio, and the Internet. They have completely changed the way people communicate forever. Even if people are alone they have a vast number of communication methods and people use these more and more as time goes on. Technology has become an integral part of our daily lives, and it has become more capable at an exponential rate. Our drive for social interaction can be considered one of the many factors that push this field of technology forwards.

Perhaps the biggest breakthrough in the field of communication technology are radio transmissions. Wireless communication technologies allow people to communicate wherever they are and whenever they want. Ever since the first commercial radio broadcasts began in the 1920s, people have built huge infrastructures based on wireless communications. After radio broadcasts came television broadcasts, and finally wireless communications. These weren’t available to the general public until the development of mobile phones and their supporting infrastructure. This enabled people to initiate communication sessions with whomever they want, and whenever they wanted. Most people know this technology by names like GSM or cellular, but the term that will be used in this paper will be Personal Mobile Communications (PMC). This term will encompass all the services we associate with using a mobile phone like making a call, sending an SMS or send/receive data. It’s a huge enabler of economic activity and it is considered a vital part of our modern infrastructure. This paper’s main focus will be PMC including its technologies, surrounding paradigm with all its rules and regulations and the medium that it uses: radio spectrum.

1.1.2: Status quo of radio spectrum

Wireless communication uses a subset of the electromagnetic spectrum called the radio spectrum in order to send and receive data. This will be discussed in more detail in the next chapter, but one of its most important properties is the radiation’s frequency. Different frequencies combined with different bandwidths get different applications assigned to them which divides the overall radio spectrum. Not every frequency is suitable for every application. This division of the available radio spectrum is necessary to some extent: if two signals are transmitted in the same geographical location and using the same frequency, they’ll interfere with each other. However, by preventing this interference through frequency dividing the overall available radio spectrum becomes scarcer. More and more frequency bands that are used for wireless communications including PMC are being more heavily used as time goes on. This means that at a given place and time, users are experiencing interference that that perceive in the form of lower call quality, or slower data transmissions. This is partly because of the limitations of technology and partly because of the number of users in a given area. Many people will have experienced slow or sporadic Wi-Fi connections at some point, or simply haven’t been able to place a call at a busy location like a city center of music festival for example.
Today, big portions of the population have a mobile phone: over 7.6 billion connections that represent 4.7 billion unique subscribers worldwide were active in 2015 (GSMA, 2016). By 2020, there will be an expected 5.6 billion unique subscribers to PMC services, and the amount of data that will be transferred will grow with almost 50% each year. Average data consumption is expected to rise to 18 GB per month in Europe in 2021 (Ericsson, 2016). This can be regarded as a major growth, and will become more problematic over time as PMC networks will become overly saturated. Another problem is that more and more people rely on mobile connections as their only broadband Internet connection (GSMA, 2016). This is caused by the widespread use of smartphones and remote areas that have no other means of connecting to the Internet.

One top of all this growth within the PMC space, there are new applications emerging today that use the radio spectrum to function. For example: cars in the EU will have an emergency system built into them by 2018 (Commission of the EU, 2011). This system will automatically send data in case of an accident to the emergency services (location, time of the accident, type of car etc.). This communication will either require available spectrum or it needs to operate in the PMC spectrum. As cars gain more self-driving capabilities, they’ll eventually be able to communicate with each other. This will require new spectrum bands, or it’ll put pressure on existing spectrum bands. Automated homes and the Internet of things will also cause more and more interference in peoples’ homes. There are many other applications like smart grids, more machine to machine (M2M) communications and so on, that will increasingly use wireless technologies. They all require new/more bandwidth or need to operate in existing spectrum bands. The world has become digital and a growing percentage of economic activity relies on telecommunications (GSMA, 2016). All of this growth increases the pressure on the already saturated PMC networks. This happens when new applications use PMC spectrum and technologies, and when they get their own bands (this limits the future growth of PMC).

1.1.3: Future developments
In a response to the higher requirements in the PMC space, standard bodies have developed new generations of technologies roughly every 10 years. These are usually focused around faster data transmissions given the same frequency and bandwidth. They are iterated upon several times within each generation, always requiring a new device to benefit from the improvements. New frequency bands are usually assigned to every major new generation of PMC technology: these bands are chosen on a global scale by standards bodies (discussed in Chapter 2). PMC is a global technology and a global market with huge network effects: any changes usually come in a top-down fashion. These decisions on what spectrum bands to use for PMC are also long-term decisions: they usually remain unchanged for several decades.

This paper will mainly focus on Europe, so a logical place to start is the European Union (EU). They have launched the Europe 2020 program in order to make the EU a competitive, social and “green” economy by the year 2020 (Council of the European Union, 2010). Underlying this program is the Horizon 2020 program: 80 billion euros of funding to reach the set goals. One part of Europe 2020 is the Digital Agenda for Europe (DAE), which included the radio spectrum plan (discussed in more detail in Chapter 3). This plan was set up to meet future requirements of PMC and other forms of wireless communications. The main points that are addressed are the usage growth including identifying more spectrum for PMC (1200 MHz of bandwidth total), harmonizing what spectrum bands are used for which application in the member states, and the fostering spectrum sharing. So far, new PMC spectrum has been added and more is planned for the near future. But the underlying system
of spectrum assignment isn’t scheduled to change anytime soon. Spectrum sharing requires new technologies, a new PMC paradigm or most likely both.

1.2: New technology and a new paradigm

1.2.1: A new way to move forward
Traditionally, all fields of technology have become faster and more capable as time went by. Think of personal computers during the last couple of decades: more processing power, more storage, more pixels on the screen etc. PMC technology has been no different: each generation has been capable of faster transfer speeds and better call quality. Mobile phones have become more capable too, from old feature phones to the smart phones we take for granted today. These are using an ever growing amounts of data. With the introduction of the latest revisions to the current generation of PMC technology (4G), users are able to transfer data at speeds that rival broadband connections. Like the case of the microprocessor, speed increases aren’t and shouldn’t be the main objective anymore. The next generation of PMC technology, often referred to as 5G, needs to incorporate means to cope with the explosive growth of the number of PMC users and the amount of data they are using. There are also many different devices that use a PMC connection, like tablets and wearables. Smart phones are people’s main device today, but this will not always be the case. New devices will come along in addition of the smartphone, and some of them will require, or at least benefit from, a cellular connection. Again, this puts more pressure on the spectrum shortage problem.

1.2.2: The cause of spectrum shortages
The main cause of the current oversaturation in the PMC space is the result of both technology and regulations. Currently the radio spectrum is divided into many different sections called bands, each allocated to a different purpose. A frequency band like the 800 MHz band for example is split up into smaller bands. Each of these smaller bands is exclusively licensed to a particular company. A government technically owns the spectrum but private companies can obtain an exclusive license for a certain time and for a certain frequency band through a spectrum auction. This is called the command and control system and will be discussed in detail in Chapter 3. A company offers their services using the bands that they have licensed. If only a few people are using these services at a given location, the radio spectrum is underutilized. This underutilization is often referred to as a spectrum hole. Even if a lot of people are transmitting data in neighboring bands, part of the spectrum has to remain un-used to prevent interference. This is referred to as a white space. Spectrum holes can be geographical by nature (not many users are in an area) or temporal (not many users are transmitting data at a certain time). Whitespaces are always present: they are created to prevent interference. This is illustrated in figure 1, which shows different parts of the spectrum being used to a different extent.
Radio spectrum is a unique natural resource, and to be more specific: it is a unique common-pool resource. Everybody can technically use the spectrum but it is rivalrous: if two or more transmitters transmit at the same frequency near each other they’ll interfere each other. There are technological solutions to this like different code based access schemes, but eventually you’ll run into a local limit. Globally however, radio spectrum is limitless and instantly renewable: if you turn off the transmitters in a geographical area, radio spectrum is immediately re-usable. This resource has some unique characteristics and requires a well-defined framework to manage them properly. This will be discussed in more detail in Chapter 4. There are several ways to do this: you can leave it open to anybody, or the owner sets restrictions on who can use it at any given place and time.

The current framework of command and control leaves the radio spectrum significantly underutilized. Spectrum utilization in frequency bands that are assigned for PMC use case can be as low as 15% at a given time of day (Akyildiz et al., 2006). This is highly inefficient, and is a result of the exclusive licenses and the general way by which radio spectrum is managed. With the continued growth in the PMC space, and all the new applications that are coming, this inefficiency can result in serious issues for all wireless applications. Current technologies and regulations in the PMC space are set up to prevent interference by putting each party’s respective application in a frequency band. This has worked well ever since the introduction of PMC services, but the number of devices that access the resource is increasing. The next generation of PMC services (commonly referred to as “5G”) could be a new framework and not just a new set of technologies. Rules and regulations can always be changed, but only if there are technological advancements that make this possible. The switch to a new generation of PMC technology offers an opportunity to rethink some of the long standing assumptions about it including the surrounding paradigm. It has remained basically unchanged since the early 90s, except for relatively minor changes that will be discussed in Chapter 3.

1.2.3: Cognitive radio
This paper will focus on a range of technologies that are collectively called cognitive radio (CR). Cognitive radio is a dynamic system that will use the best possible transmission parameters based on its configuration and input from its environment. It can optimize transmissions automatically and learn to become better over time. This technology will be discussed in more detail in Chapter 2. Its main benefit is that it can work around the current frequency band system. Imagine a system that picks up an increase in interference and moves your transmission to a frequency where there’s less interference. This can solve the problem of underutilization caused by spectrum holes and white spaces. It can also enable a whole new
There has been much research in the field of cognitive radio since an article by Mitola (1999a), which explained the concept of cognitive radio. Much of the research has been focused on filling in the whitespaces temporarily, or allowing secondary users in licensed spectrum bands. These solutions fall in line with the current command and control system. Research in the field of radio spectrum reform have generally assumed the current state of technology. They either propose more market solutions to solve spectrum shortages or they propose an open-access model as a solution. The latter one means that radio spectrum will be freely accessible for everyone to use for any purpose. This would make the radio spectrum part of the commons, which are all the natural and cultural resources that are available to all members of a society. Natural resources that belong to the commons are susceptible to overutilization (Explained in more detail in Chapter 4). This paper will try to establish a whole new paradigm with CR-based technologies at its core. Cognitive radio is an enabling technology that allows for a disruption in PMC spectrum management.

1.3: Research objective and structure
The main objective of this paper is to examine the possibility of a new paradigm in the field of spectrum management. Its focus will be the PMC field, which contains many inefficiencies and has remained relatively unchanged for a long time. This paper contains exploratory research into the application of cognitive radio in the PMC field. As will be discussed throughout Chapter 2, the technology is still under development so there are a number of unknowns that surround it. The main method has been the analysis and interpretation of relevant research papers in the field of cognitive radio and common-pool resource management. On top of that, many regulatory sources and research papers in the field of spectrum management have also been consulted. The result will be a basic new framework for PMC as well as starting point for future research and some recommendations for policy makers.

1.3.1: Research question
The main research question is as follows: Can cognitive radio technologies enable a new paradigm of spectrum management in the field of personal mobile communication?

This research question is extensive so it’ll be divided into multiple parts:

1) How can cognitive radio contribute to meeting future requirements in mobile communications?

2) What does a new framework for implementing cognitive radio look like? (i.e. what needs to change in the current paradigm of mobile communications?).

3) Will radio spectrum be properly managed by this new paradigm?

1.3.2: Relevance
As stated in the introduction section, communication is vital for our daily lives and economic activity. The growing demand and limited supply of PMC radio spectrum could result in a significant economic loss to society (Schneiderman, 2010). All members of our society benefit from a well-managed radio spectrum, so a new and modern paradigm is worth exploring. This paper will also provide a novel application for cognitive radio, which is in itself a field with many different use cases. The combination of new technology and a new
paradigm surrounding this technology will add to the discussion surrounding the future of PMC. The new paradigm will also reflect on the management of spectrum as a natural resource. As mentioned, radio spectrum is a common-pool resource (CPR). Open-access CPRs are part of the commons, free to use by everyone. There is a vast history or research in the fields of CPRs and the commons, but not much of it focusses on radio spectrum. This paper will add to the discussion of these topics by examining the nature of radio spectrum as a resource and how to best manage it from that point of view.

1.3.3: Reading guide
This paper consists of 6 more chapters. Chapter 2 will examine the technical nature of radio spectrum, the history of PMC and finally cognitive radio. It provides an overview of the technology, as well as its limitations and uncertainties. Chapter 3 will illustrate the current framework of PMC management and how it came about. It’ll discuss some alternative approaches future plans that the different actors have set out. Chapter 4 covers the following topics: the public and private goods, the tragedy of the commons, and common-pool resources. It’ll also discuss the theories by Ostrom, which were developed as a framework for managing a CPR. Chapter 5 will discuss the results from the previous chapters and build a new framework for PMC management. This will answer the main research questions of this paper. Chapter 6 will summarize and evaluate the new paradigm, and uses the findings of Chapter 4 to test the new framework. Finally, Chapter 7 will provide conclusions, discussions, and address necessary future research.
2: Radio spectrum, standards and technology
This chapter will give an overview of radio spectrum, and the technologies to access it. It’ll provide some background information on the early developments in telephone and radio technologies, before introducing a new technology that can be used to access spectrum: cognitive radio (CR). This section is mostly descriptive as it is meant to introduce the new technology that will make a new paradigm possible. The technology will not be explained in its full technical details, as there are many different implementation possibilities and uncertainties. These lie beyond the scope of this paper.

2.1: Radio spectrum

2.1.1: Electromagnetic radiation
As discussed in the introduction, PMC uses the radio spectrum to transmit information. Every transmission of information has one or more senders, one or more receivers and a transmission channel. All radio transmissions are transferred by using electromagnetic radiation as a medium: energy that is released during electromagnetic processes. This energy is made up of a combination of an electric and magnetic field that forms transverse waves. There are other theories on the nature of electromagnetic radiation such as the particle representation, but the wave representation will be used for this paper. Electromagnetic radiation always travels at the speed of light using an array of wavelength and frequency combinations (wavelength * frequency = the speed of light). This full range of wavelength and frequency combinations is referred to as the electromagnetic spectrum, often called spectrum for short. Different areas of this spectrum manifest themselves as different phenomena: some frequencies correspond to viable light, some to gamma radiation and some to radio signals. An overview of this can be seen in figure 2.

![Figure 2: The electromagnetic spectrum (Blacus, 2012)](image-url)
2.1.2: Electromagnetic spectrum

As showed by figure 2, spectrum is usually divided up into frequency bands. Frequencies ranging from 30 MHz up to around 300 GHz are considered radio waves. These are divided into different bands by different standardization institutes (discussed later). It is important to know that this division is completely arbitrary and human made. There are no physical properties that dictate these divisions, they are merely made to structure the available spectrum. These bands are often separated by whitespaces to prevent different transmissions interfering with each other. The most desirable radio frequencies are located in the Ultra High Frequency band as defined by the standards body ITU: 300 MHz to 3000 MHz (GSMA, 2014). Most of this spectrum in the EU is currently in use (ECC, 2015), and it is divided into smaller frequency bands based on its application. For example, there are bands for PMC, TV broadcasting, radio astronomy, GPS, and so on.

In theory electromagnetic spectrum is infinitely dense: there are an infinite number of frequency bands between 300 MHz and 300 0MHz. However, each channel would be infinitely small. There is a real world limit to the amount of information that one can transmit within a certain geographical area and in a certain frequency range (Ryan, 2005). This is known as Shannon’s channel capacity. This effectively turns usable radio spectrum in an area into a finite, and therefore scarce resource. Chapter 3 will illustrate the current PMC system and how it further limits they available spectrum. Usable spectrum doesn’t need to be created because it is a natural resource like water or natural gas. The key difference is that it can be re-used: there is no physical reason why you can’t transmit TV signals over a frequency at one time, and PMC services at another time. These kinds of resources (CPRs) will be discussed further in Chapter 4. Both the U.S. and the EU have classified spectrum as a natural resource, with the EU calling it an essential and scarce resource (Ryan, 2005). It is therefore important to manage it properly, and optimize this process whenever possible.

2.2: Early development and analog communications

The vast communication networks that we know today came from humble beginnings that started in the 19th century. To better understand cognitive radio and its possible implementations, an understanding about past and current communication technologies is necessary. This section will give a small overview on the different elements that lead to the mobile world we know and use every day: telephony, the telephone network, and radio transmissions.

2.2.1: The Telephone

Although telegraphs were technically the first method of electronic communication at a distance, the telephone will be the starting point for this paper. The first series of telephones were made up of a funnel-shaped mouthpiece in front of a soft membrane attached to a small piece of iron. Behind this membrane was a double electromagnet that produced current based movement of the piece of iron. This would cause corresponding currents on the other side, causing that corresponding disc to vibrate. This is illustrated in figure 3.
The first telegraph and telephone systems were based on one single line connecting two telephones. When the need to connect networks or telephones arose, circuit switching was implemented. This is the method to connect to network nodes by giving them their own dedicated telecommunication channel. Switching contributed to the possibility of a network of telephones called the Public Switched Telephone Network (PSTN). It spans the whole world via various types of different physical channels that are connected by switching centers called telephone exchanges (Anttalainen, 2003). The channels that connect users to these exchanges are collectively called the local loop. Mobile telephones also connect to the PSTN with the wireless connection to a cell tower acting as the local loop. Each user has a unique telephone number reachable from around the world and they pay a telephone operator for access to the network.

One single party called the Local Exchange Carrier (LEC) owns the local loops. Most geographical areas shared one LEC that had a monopoly in that area. In the 1980’s and 1990’s, a strong liberal sentiment in combination with privatization lead to regulation that allowed for competition on the local loop (Huurdeman, 2003). This is called Local Loop Unbundling (LLU) and the competing parties this has created are called Competing LECs (CLEC). These parties can offer services using the local loop by paying a certain price to the LEC. What that price is, or what it should be, depends on National Regulatory Authorities (NRAs). This is a public authority that exists on a national level that supervises a number of economic activities including telecommunications. The EU Council has adopted LLU for twisted pair connections in 2000, mainly to stimulate competition on the Internet market (Council of the European Union, 2000). The local loop of the PTSN is increasingly being used to connect users to the Internet, which covers the entire world and can be used for all sorts of communication applications. It has become the most important communication backbone in history.

2.2.2: Development of the radio technology

As we know today, an ever-growing number of people have access to the PSTN and the Internet from a mobile device. James Maxwell first described the propagation of electromagnetic waves in 1873 via the famous Maxwell equations. The electromagnetic spectrum is made out of different types of electromagnetic radiation, all travelling at the speed of light (in a vacuum: it can vary slightly depending on what it’s traveling through) . The lower frequency part of the spectrum consists of radio waves, ranging from about 3 KHz to 300 GHz. Many people including Nikola Tesla and Ferdinand Braun, made prototypes of what can be described as a radio, but its invention is widely credited to Guglielmo Marconi. He completed a successful transmission over a distance of 2.8 km in 1897 (Huurdeman,
This marked the birth of wireless telegraphy, and laid the groundwork for radio transmissions and wireless telephony.

Each radio consists of a number of basic components, which are illustrated in figure 5 (Anttalainen, 2003). A radio-transmitter is an electronic circuit that can convert electrical energy into a radio signal. It contains an oscillator that generates a sine wave with a certain frequency, and a modulator that adds information to this signal (Freeman, 2005). The signal is sent on a certain frequency of the electro-magnetic spectrum called the transmission channel. During the transmission there is always some amount of loss due to attenuation (losses due to the medium a signal travels through), noise, weather conditions, and interference from other signals. The receiver will have to compensate for this when translating the signal back. Both transmitter and receiver use antennas to convert the electric signal into a radio signal and vice versa. Later radios combined their transmitter and receiver into one hardware component called a transceiver.

Large-scale radio broadcasting began in the 1920’s using new vacuum tube transmitters that could produce continuous analog waves (Huurdeman, 2003). These were first transmitted using Amplitude Modulation (AM), and later via Frequency Modulation (FM). There is also the possibility for phase modulation, often used in radar systems and polarization modulation, often used by radio astronomy. Anyone with anyone with proper equipment could technically broadcast signals and receiver radio signals. This is limited however by legislation, which will be discussed in Chapter 3. Radio technology was relatively quickly applied to many other functions, such as TV broadcasts, two-way radios, radar, and navigations. Analog mobile communication systems, now known as 1G, were developed in the 1980’s. There were nine competing standards to begin with (Selian, 2001), but the Nordic Mobile Telephone (NMT) in Europe was one of those but turned out to be a successful first PMC system. Despite being limited by its analog technology, it reached its capacity in a couple of years after its launch in
People realized that standardization was necessary in order to enable the capacity of these PMC systems to grow. Another limiting factor were the analog signals: digital signals are capable of much higher information density. They have multiple other benefits like more robustness and security benefits. The real start of PMC systems for most users came with the GSM standard.

2.3: Digital technologies and access

2.3.1: Standardization
An important understanding when developing large-scale deployment of technology is standardization. When people use technology to communicate it’s necessary that their devices interoperate properly. To facilitate this, people confirm to telecommunication standards: technical specifications or criteria that are to be followed to ensure that products, processes, and services are fit for their purpose (Gokhale, 2004). Various institutions define standards that other institutions, companies or entire countries can or have to adopt. Private companies can also define networking standards and have done so. The following standardizing bodies are relevant in the area of general telecommunications and PMC:

1) International Standards Organization (ISO)
Founded in 1947, ISO aims to promote the development of standardization and related activities in the world. The aim to facilitate the international exchange of goods and services and developing cooperation in the spheres of intellectual, scientific, technological, and economic activity (Gokhale, 2004). Virtually all countries in the world are either a member or subscribe to their standards. One of their main contributions in the field of networking is the Open Systems Interconnect Model (OSI Model). The lowest 2 layers are often based in hardware, while the rest are based in software. This model is illustrated in figure 6.

![Figure 6: The OSI reference model (Anttalainen, 2003).](image)

2) Telecommunications Union (ITU)
The ITU is an agency that was established in 1865 that coordinates the global use of radio spectrum, and promotes cooperation in the development of technical standards (ITU, 2015). It has been a specialized organization of the United Nations since 1947. They cover all sorts of communication like broadband, satellite, TV broadcasting and of course mobile communications. The ITU helped with the standardization of various PMC standards, namely the 3rd and 4th generation.
3) Institute of Electrical and Electronics Engineers (IEEE)

The IEEE is an association of electronic engineers that aims to improve the areas of electrical/electronic engineering, computer engineering and telecommunications. It has a Standards Association (IEEE-SA) that produces standards recognized by both the ISO and ITU. Most notably they’ve produced the standard for Local Area Networks (LAN), and Wi-Fi (802.11). Their members have also contributed many scientific papers about cognitive radio.

4) European Conference of Postal and Telecommunications Administrations (CEPT) and European Telecommunications Standards Institute (ETSI)

CEPT is a European conference created by former monopoly holders in the areas of postal and telecommunications (CEPT, 2013). They have established a telecommunications division called the Electronic Communications Committee (ECC), and they set up ETSI in 1988. This is a separate standardization organization that creates global telecommunication standards (ETSI, 2015). They’ve created the 2G GSM standard, and in cooperation with the ITU, produced the 3G (UMTS) and 4G (LTE) standards.

The 2G GSM standard was developed by ETSI under direction from the then existing European Economic Community (EEC). They wanted to create one single European communications market, and become the leading supplier of PMC technology (Agar, 2013). This endeavor proved very successful as GMS was adopted worldwide, with the exception of Japan and South Korea. It was even partially adopted in the US, which had developed its own technology in the form of IS-95 or CDMAOne. The 3G standards were developed by the 3rd Generation Partnership Project (3GPP): a collaboration of various standardizing bodies from all over the world (Anttalainen, 2003). There are non-GSM based 3G standards in use, mainly those developed by the 3rd Generation Partnership Project 2 (3GPP2). This became CDMA-2000: the 3G standard for parts of the U.S., China, India, Japan, and South Korea. The 3GPP2 partnership was discontinued, when the members involved favored Long Term Evolution (LTE), which is a part of the 3GPP, for their 4th gen network. LTE is the first true global PMC standard, since virtually the entire world has adopted it.

2.3.2: Personal mobile communications and access

This paper will use the GSM “family” of technologies as its basis since they are the most widely adopted today. A basic GSM network is illustrated in figure 7. Phones connect to a Base Station Controller (BSC) via a Base Transceiver Stations (BTS): this system will be referred to as the base station. This subsystem handles both connection and call handoff, when you move from the coverage area of one to another. They are the antenna towers you see through the world. Base stations span a coverage area, known as a cell that provides service to the user on a certain frequency of the radio spectrum. The actual link between a BTS and a phone is called the air interface. This is the wireless part of the connection between two users and is represented by the lowest two layers of the OSI model. When a user leaves a cell and moves to another, the connection is seamlessly handed off by the system. Base stations connect to a hub, the Mobile Switching Center (MSC), which can switch calls to the PSTN and allow users to send and receive SMS messages. The rest of the switching system controls things like subscriber location, which users can use the network, security etc. This is necessary, as users need to be billed and base stations needed to know when to perform handoff (Agar, 2013).
The initial GSM networks were used for calling and sending texts. Today, users have steadily shifted to using their mobile phone for Internet access. Users can connect to the Internet, starting with “2.5G” (GPRS) networking. BSCs connect to a GPRS node as well as a MSC to provide a data connection. These nodes serve as the bottom 2 layers of the OSI model. These data connections were later extended by a new generation of technologies called UMTS (3G). It used faster air interfaces, but shared the same core network principles with GSM (a combination of circuit switched voice and packet switched data). Later networks called Long Term Evolution (LTE or 4G) adopted even faster air interfaces and used packet switching only. In order to make an “old fashioned” phone call via the PSTN, user equipment would have to fall back on a 2G or 3G connection. This is currently being remedied by the development of Voice over LTE (VoLTE). All mobile phone generations do share the same principle access method. To access a GSM based network one needs Mobile Equipment (ME), and a SIM (Subscriber Identity Module). They connect to the base stations of your Mobile Network Operator (MNO). The MNO is the party that builds and maintains an infrastructure of base stations and provides a user with Internet and phone service. They use a set of frequencies that they have licensed, which will be discussed in more detail in the next chapter. They also bill the user, usually on a monthly basis.

Early radio systems like an early two-way radio can either receive or transmit data at a given time. Full duplex systems like PMC systems and Wi-Fi can do this at the same time, but the signal need to be separated in order to function properly. Frequency Division Duplexing (FDD) divides this functionality over different frequency bands: one is used all the time for receiving data and the other for transmitting it. This makes sense in the world of phone calls: you have as much speech “data” going in as you have going out. The main GSM and UMTS implementations used FDD as part of their air interface standard. LTE can work with both a FDD air interface and a Time Division Duplex (TDD) one. TDD divides receiving and transmitting in the time dimension, by quickly switching between transmitting and receiving data in the same frequency band. FDD systems are typically more resilient to interference and provide real simulations transmission and reception (Chan et al., 2006). They suffer in terms of performance due to the separated channels and they are less flexible because they require a large guard band to prevent self-interference. FDD systems also have higher...
hardware costs. TDD based systems can function on any one main channel and they are more flexible. If a situation requires more download than upload (which is common in IP-based traffic), more time can be allocated to that. However, they are more prone to interference, especially if one neighboring base station is receiving data and another base station is transmitting it at a given time (Chan et al., 2006).

2.3.3: Wi-Fi
Another common use for radio technology besides PMC is connecting users to the Internet via a Wireless Local Area Network (W-LAN or Wi-Fi). People use it in their home to extend Internet access to all of their wireless devices. A growing number of businesses and public places offer free Wi-Fi as well. Wi-Fi is used in frequencies within the 2.4 GHz and the 5 GHz bands. These bands are license free, which means that anybody can buy a transmitter and use it if it’s used for certain applications like for instance Wi-Fi. Other restrictions apply to manufacturers of transmitters, mainly regarding transmitter power. These are determined by either a national government or in the case of Europe by the EU (Council of the European Union, 2014a).

2.4: New use-cases and cognitive radio
This section will give an overview on cognitive radio, and how it can help with future requirements for PMC and spectrum management. The basic functioning of the technology is explained, as well as its current limitations. Some attributes of the technology will have to be assumed because the technology is still under development, but this will be avoided where possible.

2.4.1: Software Defined Radio
Software Defined Radio (SDR) is an implementation of radio where many typical hardware components like modulators, amplifiers, and filters have been replaced by software (Sadiku & Akujuobi, 2004). The concept is fairly old, but recent technological advances have made economically sound implementations possible. It consists of a digital signal processor, an ADC/DAC converter, and a reconfigurable antenna. Signal processing therefore takes place in software instead of a specialized electronic circuit, allowing for changes in e.g. modulation and operation protocol (the lower levels of the OSI model). A reconfigurable wideband antenna allows the SDR to change its frequency of operation among other things (Mitola 1999b). A schematic of a typical SDR transceiver is shown in figure 8.

Figure 8: SDR transceiver (Akyildiz, et al., 2006)

An example of simple SDR based receiver is a modern FM radio. You drive your car across the country, and the radio changes its frequency so you can keep listening to the same radio station. These properties provide a starting point for cognitive radio. Cognitive radio (CR) is a new use case for SDR radios, or rather a system built on top of SDR. It involves using many of SDRs together in a network, allowing them to decide for themselves what frequencies (and
other parameters) to use. It’s important to note that SDR and CR don’t specify an air interface like for instance LTE does. These can be developed independently from each other.

2.4.2: Cognitive radio and the cognitive cycle

The main goal for cognitive radio (CR) as far as this paper goes is dynamic spectrum management (Haykin, 2005) and variation thereof. This is a concept that aims to optimize spectrum usage by sharing spectrum to other parties when it is not in use. This can be the key to solve growing spectrum shortages. This paper uses the CR definition given by Haykin (2005):

- Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment, and uses the methodology of understanding-by-building to learn from this environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier-frequency, and modulation strategy) in real-time, with two primary objectives in mind:
  1: highly reliable communications whenever and wherever needed
  2: the efficient utilization of the radio spectrum.

CR learns by analyzing its surroundings. Basic data points including things like its location, time of day, type of network it’s in, and where/how many other radios there are. Other parameters a CR system can detect are radio transmission characteristics: RF stimuli. These are things like waveform characteristics, operating frequency, spectrum holes in its area, and noise. This data is analyzed, which provides information about the RF environment. The RF environment contains spectrum holes in the area, traffic statistics and information about the current noise floor (all unwanted signals combined). A typical CR system uses data from numerous transceivers in its surrounding area, both cognitive and “regular”. All of this information can be used to construct the interference temperature: a metric that provides data about sources of interference in a particular area (Haykin, 2005). The interference temperature limit is the characterization under which the system can still provide satisfactory QoS. Finally, all of this information can be used to change its transmission parameters like transmission power, central frequency, and bandwidth (Tragos, Zeadally, Fragkiadakis & Siris, 2013).

Currently, frequency is divided up into bands that are determined by human decision and not by any law of nature. When you say: “my Wi-Fi router uses the 2.4 GHz band”, you are actually saying it transmits and receives data between 2.412 GHz and 2.462 GHz. Those bands are decided on by recommendations of the standards bodies like ITU and policy set by the EU and national governments. A CR system can (from a technical point of view) choose any specific central frequency and any bandwidth to surround that central frequency, making it much more flexible than the current frequency band system. It can also change its air interface if necessary, switching between different duplexing and modulation techniques. This further increases the possibilities of CR to provide an optimal connection at all times.

A CR system can be reconfigured dynamically and even more important: it can reconfigure itself. Recent advancements in technology (mainly digital signal processing and compute power) have made this possible. CR saves computation power that regular SDR wastes because of its intelligence (Mitola, 1999a). By learning from typical scenarios it encounters every day, it can predict what the optimal actions are given certain inputs using statistical and mathematical methods (Axell, Leus, Larsson & Poor, 2012). The process of finding the optimal transmission settings given the current state of other transmitters in an area is the
most difficult and vital part of a CR system. Different methods to solve this issue involve iteration and the use of heuristics, game theory, and evolutionary algorithms (Tragos et al., 2013). Game theory is an analytical tool to analyze the behavior of self-acting parties with self-interest. Analysis with different parameters like the “aggressiveness” of a transmitter and noise thresholds can be used to improve a CR system. Evolutionary algorithms mimic evolution and social behavior to develop generations of optimal spectrum assignment parameters. These are then used as the starting point for the next generation.

By using these various techniques, a CR system will improve its ability to optimize spectrum use. This is a form of machine learning: the system iterates towards better and better actions. Once the system has decided what the best course of action is it can alter its transmitter’s parameters if necessary. It can also communicate those changes to other radios in the area, so they can update their data. All of the functions of a typical CR setup work together in what is known as the cognitive cycle (see figure 9). This is a framework proposed by Mitola (1999a) and further elaborated by Haykin (2005) and Akyildiz et al. (2006).

Figure 9: A basic cognitive cycle (Haykin, 2005)

2.4.3: Spectrum holes

CR was originally developed as a way to facilitate the filling of spectrum holes as described in the introduction. Typical CR networks are represented as a secondary network to an existing one (Tragos et al., 2003). Think of a cell tower operated by MNO A in a location where the majority of people subscribe to services by MNO B. The spectrum that A licenses is underutilized, while the spectrum licensed by B is heavily in use. This leads to underused spectrum, as well as poor service for the users of B. A CR system would learn over time what spectrum is underused at what time. It could automatically let users of B use the spectrum bands of A, and switch them back when A’s primary users need the spectrum again. There also have been propositions to use CR technologies to fill up whitespaces (Axell et al., 2012).

The filling of spectrum holes is a great method of utilizing the spectrum more efficiently, and proofs of concepts are already available today (Badoi, Prasad, Croitoru, & Prasad, 2011) (Matsumura et al., 2015). Studies have also shown that it can be done with sufficient QoS (Chan, Lin & Chou, 2015). There is newer application of CR available to us: spectrum sharing.
2.4.4: Spectrum Sharing

Spectrum sharing is a fair scheduling method for all coexisting users. This is different from the CR application that is discussed in most papers (filling spectrum holes by allowing secondary users). All users start out as equals, and use the best transmission parameters possible based on the RF environment. This is a step beyond the filling of spectrum holes: CR-based spectrum sharing will result in a new paradigm of spectrum management.

Spectrum sharing can be set up in a number of configurations. The first one is a centralized vs. a distributed network (Tragos et al., 2013). Centralized networks control a larger area, and they share data about spectrum allocations between all of their nodes. The decisions surrounding the parameters are made by a centralized server. This is particularly useful for PMC as users move around between different nodes of the network. They also are well suited for systems that need to learn over time. This system will require a lot of investment to make it robust enough. Distributed systems manage themselves and are often used when a new infrastructure isn’t feasible: the CR node is the exception rather than the rule. Distributed CR nodes make their own decisions. They can make these decisions faster and aren’t as prone to widespread failure, but don’t offer the benefits of a fully centralized system in terms of learning. They also require more capability.

Another important difference is cooperative vs. non-cooperative CR systems. Cooperative spectrum sharing nodes take other nodes into account when claiming or releasing spectrum. They are aware that their actions influence other nodes in their network. Non-cooperative nodes do not do this and can be considered “selfish”. If CR is to be used in a PMC context, a cooperative system is definitely preferable. The best result is achieved when all of the transmitters in a geographical area work together. Whether or not the setup is centralized depends on the type of spectrum management that is chosen. A centralized system or at least a centralized server, will provide the most benefit in terms of optimal network performance. The base stations of the current infrastructure provide a logical start to place centralized decision making/learning servers. There are other more technical parameters to consider, like whether or not to use a common control channel that is specifically used for signaling or whether to use a segment based or a cluster based system (Tragos et al., 2013). These technical decisions are still being debated and may require real world testing in order to make those decisions.

So, how can spectrum sharing work in practice and in the context of PMC? Let’s say a user is communicating in a certain area on a certain frequency. He drives home from work into an area where that frequency is being use heavily. The RF stimuli are analyzed by the radio that concludes in the exceeding of the interference temperature limit. At the same time, the radio finds that another part of the spectrum is underutilized. The user’s connection will be moved over to that part of the spectrum. After some time, the system learns that every weekday, that user moves from his work back to his home. Even though there is enough radio spectrum available where he works, he is moved over before he leaves. This avoids temporary interference. It also saves computational and transmission power, as the transmitter can keep operating at the lower power level. Better and better algorithms will be developed because of the learning capabilities of the system. There are several new technologies for air interfaces like smart antennas, which follow users to direct signal better so the system needs less transmission power. Ultra-wideband is another option: this operates in small bursts below the noise floor. These technologies are also being considered for 5G implementations, sometimes alongside CR (Networks, 2011). CR can be the foundation on which other connection
technologies are built. This paper will not go into the details of the specifics of the air interface: it focusses on a framework based on CR.

2.4.5: Benefits of cognitive radio

As discussed in the introduction section, useful spectrum is heavily causing more congestion in busy parts of the radio spectrum and busy geographical areas. But because a band is licensed to one party for a long time, that same part of the spectrum could sit idle and thus go to waste. Networks that can reconfigure themselves based on cognitive radio will increase the available spectrum at a given time and location. As the supply of useful spectrum grows because of this better utilization, the price of spectrum access will naturally come down. A nation-wide PMC network also requires a big infrastructure with increasingly complex architectures. Every new generation of PMC technology will require significant investments in order to be implemented, the capital expenditure (Capex). However, the operational expenditure (Opex) could become lower as CR systems learn over time. They become better at predicting what spectrum and transmission power is needed at what time and at what locations. They organize themselves, which requires less maintenances and decreases operational overhead. Once an area has been fitted with CR-based base stations and users start to use CR-based devices, PMC networks can more easily be reconfigured for new situations or requirements. This simplifies future changes to the network. On top of that, the learning capabilities of a CR network will allow it to improve its ability to reconfigure itself and it will become better at finding the best configurations based on certain parameters or requirements.

There are many new applications emerging today that use or will use wireless communications. Some of the applications often use the PMC standard and connect via an MNO to function. While the smartphone is the most important device now, this will not always be the case. They are “matured” devices, and so this paper will take them as the main device that people use on PMC networks. CR technology and the new paradigm can always be expanded to other devices if the technology allows it. Other applications that have their own standard could use PMC spectrum opportunistically. Base stations could theoretically communicate to other applications what spectrum is available at a given time and location. The Radio-communications Agency (Agentschap Telecom, AT) of the Netherlands for example, mentioned cognitive radio in a report about wireless application in the transport and logistics sector for example (Stratix, 2015). Self-driving cars could use spectrum holes to send data to each other on a timely basis. The introduction of the Internet has led to more and more applications moving from their dedicated technologies to Internet based protocols. Activities like watching TV or voice/video calling can all be done over the Internet and thus over any IP-based radio network. PMC is also moving to Internet-only technology because of its flat rate for all services, and to make the technology more simplistic (Elsner & Weber, 2014).

As mentioned in the introduction, it’s not only about faster speeds anymore; it’s about new uses for spectrum and new ways of managing it. CR can facilitate a new form of spectrum management as well as help to meet future requirements. Ryan (2005) used the term sustainable consumption in regards to radio spectrum. The term is borrowed from environmental studies and indicates the amount of a natural resource that can be consumed without any risk of depletion or damage to the environment. In terms of radio spectrum, this term is about the amount of information that can be transferred without any harmful interference. CR can significantly raise the sustainable consumption of spectrum and by doing so help solve the problem specified in the introduction.
2.4.6: Uncertainties and current research

Much of the underlying technology of cognitive radio is still being developed today. Several CR standards have been proposed by different organizations, but no “winner” has surfaced yet (Tragos, 2013). On a technical level, there are still balances that need to be found in many areas that include interference, spectral efficiency, spectrum characterization, fairness, energy efficiency, and delay. Other factors like user behavior need to be modeled and tested in the real world before any large-scale implementation can take place. Tragos et al. (2013) gives an overview of the research that is being done in these areas. The consensus is that there is still work to be done but there is an opportunities of a fully cognitive communication system. As discussed, an important part of a CR system in the context of PMC is cooperation: all nodes (all base stations and mobile phones) should work together to achieve this configuration. This calls for a full transition to CR based systems in the PMC space. While this is unlikely in the short term, this is something that should be strived for in the long term.

The most important use for CR in this paper is spectrum sharing. Spectrum sensing is an important part of this equation: this is the process that gathers data about RF-stimuli. The papers used to define CR identified this process as a potential issue since it could interfere with ongoing radio transmission. Recent studies have shown that this process is becoming more and more efficient (Axell et al., 2012) (Quan, Cui, & Sayed, 2008), up to a point where this issue will no longer exist. This allows for both efficient spectrum sharing and for spectrum holes to be filled properly without interfering with existing users. Game theory is an important and promising method of decision making in a CR system. Research showed several strategies for reaching efficient spectrum use in large geographical areas using game theory (Wu, 2014). This is specifically important in the case of PMC. Another important area of CR is the performance of the system as a whole. There are a lot of recent advancements in areas like statistical analysis that increases throughput of CR system (Zhu, Shen, & Yum, 2007) and grouping similar devices together and giving them similar access schemes to prevent interference (Chatzikokolakis et al., 2015).

Research has even started to focus on CR system specifically for PMC (Lien, Chen, Liang, & Lin, 2014), showing that CR can be used for the next generation of PMC. Cognitive systems can also co-exist with traditional LTE systems (Danneberg, Datta, Festag, & Fettweis, 2014). This will allow for an easier transition period, which is necessary because devices and infrastructure will not be replaced overnight. For a CR-based PMC system to work, mobile phones will have to have some spectrum sensing capabilities. Research has already shown proof of concepts of phones with spectrum sensing capabilities (Dejonghe et al., 2010). All of this research shows that there is a great interest in CR-based technologies and suggests that a new spectrum management paradigm may no longer be hindered by technical limitations like it has been before. Spectrum management can potentially shift from a policy centric approach to a more device centric approach. Even with Shannon’s channel capacity being present, CR systems can utilize spectrum so efficiently it becomes much more abundant. There are no guarantees unfortunately until large scale testing of a CR-based PMC system starts.

2.5: Main points from this chapter

- The radio spectrum has a practical limitation as to how much information can be transferred in a given spectrum band.
- Radio communications have been around for a long time and are vital to our daily lives and economic activity.
- Standards bodies are an important part of moving PMC forward.
- Cognitive radio (CR) is a self-configuring SDR system that sets parameters based on the input it senses as well.
- CR gets better over time through learning, and optimizes spectrum usages while maintaining a sufficient QoS.
- CR can be used for filling spectrum holes and spectrum sharing, which can both help with the spectrum shortage problem. It can also solve interference issues if many users of one MNO are present in the same geographical area.
- There are still uncertainties due to the lack of testing, but research suggests a promising future for CR technologies.
3: Governing spectrum and spectrum access
Chapter 2 covered the technical aspect of spectrum access. The non-technical side consists of regulations and a market to gain access to spectrum. Since spectrum is such a vital resource, managing access to it is an important issue. Current technologies and the necessary creation of fixed spectrum blocks have led to an increase in scarcity. This has resulted in a framework designed to deal with spectrum as a limited common-pool resource. However, this model is old and might possibly be outdated as a result of new technology and lead to a lower level of sustainable consumption of spectrum (Ryan, 2005).

3.1: Spectrum management and spectrum policy

3.1.1: History of PMC spectrum management
In order to get some perspective on current spectrum management, it is useful to understand how the current legislations in Europe and the U.S. came to be. Much of this history was made in the U.S., so this paper will look at this in addition to the EU. Spectrum management is defined by Bauer (2002a) and seeks to address three problems: 1) The allocation of the right spectrum for a use case, 2) the assignment of this spectrum to certain groups, and 3) the adjustment of these allocations as technology and markets evolve. This is done to maximize the social welfare that can be gained from the available radio frequency. Proper spectrum management adapts to new developments in technology. This should be done both internally (the efficient use of spectrum given a certain set of technologies) and externally (allocating more spectrum whenever possible) (Bauer 2002b). An important distinction in the field of spectrum management is spectrum allocation vs. spectrum assignment. Spectrum allocation is the process of deciding what part of the radio spectrum will be used for what purpose. For example, any frequency between 800 MHz and 960 MHz will be used for PMC. Spectrum assignment is the process of assigning (exclusive) usage rights of a part of the spectrum to a particular party. For example, the spectrum between 925 MHz and 930 MHz has been assigned to Vodafone Libertel B.V. from 2013 until 2030 to use exclusively in their PMC network.

Before there was any form of spectrum management system in place, everyone was free to access the radio spectrum at his or her leisure (Ard-Paru, 2010). Ever since Marconi’s first transmission in 1897, people could set up transmitters and receivers and transmit information over any frequency. The technology was very new, so practical applications were severely limited. In the 1922 the US government decided hand out licenses that allowed people to broadcast, which lead to the creation of radio stations. More and more radio station popped up, quickly using up much of the ideal spectrum. It was basically a free for all: attempts were made to restrict licenses, but these were rejected by courts for having no legal basis (Ard-Paru, 2010). People could effectively hoard spectrum, leading to overuse and interference. It was a classical tragedy of the commons scenario (this will be discussed in Chapter 4).

The attempts to regulate spectrum let to the U.S. Radio Act that passed on February 23, 1927 (Ard-Paru, 2010). The US’ government would assign wavelengths, and determine power and location of transmitters to combat interference. The name Radio Act reflects that only radio was considered at the time, but the same rules applied to early television broadcasts as well. The government also decided which licenses were renewed and which weren’t. This gave them much power over the radio spectrum. This paradigm is known as government control. In that same year (1927), the Consultative Committee on International Radio (CCIR) was
formed in Europe. They merged with ITU in 1934, which was the start of international cooperation in the area of radio spectrum.

In the 1950’s, more and more people began to question the central government controls approach to spectrum management. Economist Ronald Coase proposed a new paradigm: spectrum should be treated as a market (Coase, 1959). Radio spectrum, he argued, is a scarce recourse with a limited supply and demand and therefore a market should determine the price of it. Government control should be abolished, and spectrum that was bought by a party should come with property rights. Parties that bought radio spectrum bands were to be given full ownership of that part of the spectrum. This would allow investors to trade, split, combine or otherwise modify spectrum. Such market based approaches to spectrum are still discussed and rely on the notion that spectrum is scarce. The paradigm will be referred to as the market approach.

A full market approach with spectrum ownership never came to be. Starting in 1992, GSM was deployed in Europe with licenses being issued by governments (Selian, 2001). These were often given to their nation PTTs first and third parties were often required to put in a financial bid as well. These so called “beauty contests” almost always worked in favor of a PTT. In 1993, the U.S. congress permitted the FCC to auction off spectrum access (Ard-Paru, 2010) with the EU following with 3G auctions. However, they did not come with property rights as envisioned by market proponents. Spectrum remained owned by the government, and spectrum access auctions only give a usage monopoly to a party for certain time frame (more on this in the next section). This form of spectrum management, referred to as command and control, became the main system for PMC worldwide. It was mainly justified as the best method to combat interference (Akalu, 2006), and it provided a source of income for the government and therefore the public.

3.1.2: Relevant actors in spectrum management
Current spectrum management for PMC is very similar across the world: they mostly follow the command and control approach. In the EU, each member state can auction off spectrum for PMC at its own discretion, but countries have worked together to make better use of spectrum through cooperation. The ITU constitution does state that every nation has the right to regulate its own radio spectrum, like the US was doing (ITU, 2012). Practical flexibility on a per country basis is limited: there is no incentive to do things differently than neighboring countries or economic partners. The Council of the European Union has encouraged harmonization and best practices since the start of command and control auctions (Sutherland, 2007).

Governments generally enforce decisions made by the World Radio Conference (WRC) of the ITU. The way our spectrum is being used today was largely decided by the WRC. Approximately every 3 to 4 years a WRC is held by the ITU. At these events, its members decide how spectrum is divided up and what parts of the spectrum will be used for what purpose (allocation). Member countries and organizations like the EU push their own agenda at these conferences on topics like more technology independent spectrum assignments (Sutherland, 2007). There’s also an organization that promotes the interests of the MNOs called the GSM Association (GSMA) that lobbies with the various levels of government.

3.1.3: Current spectrum management and policies
In 1996, the European Commission forced each member state to create a proper market for license holder by created equal conditions for all players (in line with the LLU). This took shape at the start of the 21st century, with many new private parties licensing spectrum.
However, when the licenses where auctioned off for 3G (UMTS) spectrum, each member state took a slightly different approach. There was little to no pressure for a certain country to roll out 3G similar to any other country. Some still used beauty contests, while others auctioned off the spectrum. The amount of money that was ultimately paid by the carriers varied heavily as well (Selian, 2001). The push for 3G came mainly from MNOs and device manufactures that wanted to “conquer the world” instead of facilitating interoperability. In order to create more consistency between the different member states, the EU implanted an access and framework directive in 2002 (Council of the European Union, 2002) and later amended it in 2009 (Council of the European Union, 2009). These directives were the start of a proper, single European spectrum policy. They also laid down the tasks for National Regulatory Authorities (NRA) (Akalu, 2006). These are independent entities that look after consumer interests and intervene in the case of market failure. They provide feedback to the commission on how the commission’s decisions affect the national landscape of their respected country.

As part of the Digital Agenda for Europe (DAE), the EU established the Radio Spectrum Policy Group (RSPG) and a Radio Spectrum Policy Programme (RSPP) (Council of the European Union, 2012a). This is a roadmap for the EU’s spectrum management policies. Through this, the EU now sets up policy objectives like what spectrum to allocate for what purpose. It also priorities the harmonization of spectrum bands across its members. In 2012, the EU also passed a directive on roaming to shape the EU into one internal spectrum market (more on this in the section 3.2).

Frequency bands don’t naturally exist but they are defined by standards bodies and policy. Along with their definition, they get characteristics attached to them (Dunnewijk & Hultén, 2007). As said earlier, the ITU defines the radio bands (spectrum allocation) along with their whitespaces. Next, it’s decided if a band will need a license or not. License free bands are used all sorts of applications: some of them are used for remote controls, others for Wi-Fi, and so on. These are restricted at a device level in terms of their transmission power. Next, spectrum that will require a license is often designated for a single type of activity: broadcasting television, PMC, communications for a department of defense etc. After all these decisions, the PMC bands are licensed out by auction to interested parties (see section 3.2). Today, they often get a certain technology attached to them for example: the 2100 MHz band in the EU has mostly been licensed for the implementation of UMTS (3G). They have other restrictions as well: licenses are only given out for a fixed time period, and license holders have an obligation to build a network with certain requirements within a certain time frame. This is to ensure that licensed bands don’t remain completely unused.

3.1.4: Upcoming changes in spectrum management

As recommended by Bauer (2002a): proper spectrum management should evolve over time as new technologies emerge and markets slowly change. Ever since the launch of the RSPP in 2012, the EU has been on a path toward changing the PMC landscape by means their policies. They’ve done this by proposing more market based solutions like spectrum trading or allowing for secondary users (discussed in section 3.2). As discussed in the introduction, their main motivation is to handle the growth that is still taking place in mobile communications. If CR is ever going to be a part of future PMC, it will not be sufficient to develop a new standard that incorporates this. Legislation and policies have to be in place to facilitate this as well. The current paradigm that exists as a result of current legislation, was built up over many years with old technologies in mind. It will not be suitable for a radical new technology like CR.
As seen in the introduction, an important goal was to find 1200 MHz of spectrum for PMC. Part of this comes from digital dividend: a term used by the EU that indicates part of the spectrum that are freed up by moving to digital platforms for radio and television broadcasting (Council of the European Union, 2012a). Another big part of that spectrum could come from using currently used spectrum more efficiently. There is a start in that the ITU and EU allow for more and more technology independent bands for PMC. The auctioning of the 800 and 1800 MHz bands and the re-auctioning of the 900 MHz band in de EU was done technology independent: license holders can use it for 2G, 3G and 4G (Agentschap Telecom, 2013).

An important part of the RSPP is the facilitation of spectrum sharing wherever possible. Steps have already been taken to achieve this (Commission of the EU, 2014). A possibility for filling it spectrum holes and whitespaces is called Licensed Shared Access (LSA) by the EU. This is a framework that would allow secondary users to use licensed spectrum when the primary user isn’t using it at a certain time. Secondary users would have to obtain a separate license for each band. This could provide some solutions for frequency bands that are underused in certain geographical areas. However, this type of licensing has proven troublesome in the past due to technological constrains. This can be solved with CR but it still doesn’t use spectrum as efficiently as possible. It locks secondary spectrum use for a certain time to a certain user, just like primary license do. This makes it slow to adapt to changing conditions and requirements (Elsner & Weber, 2014).

Another option is to open up the spectrum more. The overall view is that technology can manage spectrum more and more, and by doing so needing less strict policy. Open spectrum is sometimes referred to as Collective Use of Spectrum (CUS) by the EU’s policy documents. This form of spectrum management seems to fit in conjunction with CR. It was developed with short-range devices like Wi-Fi in mind. The only limits are transmitter limitations. These are set by the EU on the recommendations of standards institutes like ETSI (Council of the European Union, 2014a/b). The EU is currently investigating means to expand this model to allow for more flexible access to PMC spectrum. Unfortunately, real efforts to move away from a command and control system for PMC haven’t been reflected in policy. This may be because of technological constraints: current air interfaces are set up with frequency bands in mind. A more likely reason is the resistance from parties invested in the status quo. It’s easy to imagine that MNOs will not be happy to lose exclusive access to parts of the spectrum. In order for CR based technologies to function in the PMC space, spectrum management needs to move to a more device centric approach.

3.2: Gaining access to spectrum: the market

3.2.1: Markets, supply, and demand

As shown by the previous section, accessing most of the radio spectrum isn’t as straightforward as buying some spectrum and start using it. All these regulations were put into place for a reason, one of them being the proper facilitation of access to spectrum. Spectrum is, for all practical purposes, a scarce resource in today’s technical regime and today’s technologies. A scarce resource is usually managed by market mechanisms: a procedure in which two or more parties engage in the trading of goods and services. But spectrum isn’t a private good: it’s a common-pool resource. It is therefore subjected to heavy regulations making it its own unique type of market. A theoretical perfect market (that is completely free and competitive) has easy entry and exit for parties, no public goods, and no potential for monopolies. None of this is the case with of radio spectrum.
Scarce resources have a supply and demand, which leads to a price. The supply of spectrum technically comes from nature since it is a natural resource. From the perspective of the spectrum market, the supply comes from the people as they collectively own it. The people are represented by national governments that are in turn guided by standards organizations and political unions like the EU. Supply has to be finite for a good or service to have a price. Spectrum is technically infinite: there exists an infinite amount of frequencies between two frequencies. How much useful spectrum is available depends on technology and the way spectrum is managed.

Spectrum demand comes from any party who wants to utilize the spectrum. This includes people at home that have Wi-Fi, television broadcasters, and most importantly the MNOs that want to license PMC spectrum bands. There is also the option to become a Mobile Virtual Network Operator (MVNO) because the wireless local loop is unbundled. These are companies that offer PMC services to end users, but they use a MNO’s infrastructure to do so. Finally, there are device manufactures, but they don’t have much to contribute to spectrum allocation: they must simply follow the restrictions set by the various levels of government. They have some influence on the progression of the different generations of PMC standards (2/3/4G). Devices have to be technically capable of transmitting and receiving using the new standard, while being a device that users can practically use and would want to buy.

3.2.2: Spectrum auctions
MNOs and parties that want to become MNOs, want to license spectrum to do so. Some frequencies bands in the radio spectrum aren’t used for communication at all, like the ones set aside for radio astronomy. Frequency bands for things like national defense, police communications etc. are obviously used but aren’t accessible to market parties. The rest of the spectrum is accessible by market players, mostly by obtaining a license. National governments give these licenses to different parties in the name of the public. After the ITU, the EU, and CEPT make their decisions, each country’s government sets up a frequency plan for radio spectrum. Since the EU’s 1996 decision, an auction for licensed bands has to be open to all market players.

Interested parties can file an application when an auction is being held in a country. They have to meet certain requirements like being a legal entity in that country and have enough capital to build out a network in case they obtain a license. If they are allowed into the auction, they can start to bid on different frequency bands. This process can take anywhere from a day to a couple of months depending on the scale of the auction. When the auction is over, the winning parties obtain the exclusive license to that band for a certain amount of time (determined before the auction started by governments). Usually, these licenses have network requirements attached to them e.g. reach x % of the population in y number of months and they must meet certain QoS requirements. Because everyone can bid on each frequency block, the final allocation of spectrum can look very fragmented. An example is the situation in the Netherlands after the last spectrum auction (figure 10).
Once the auction is over, the winners have a certain amount of time (specified in the auction’s participation requirements) to build up their new networks. In exchange for all this work, they get to charge people for access based on things like call time and data usage. They often lock down customers by offering a discounted phone in exchange for a one or two-year commitment. Another option is to let the customer bring his or her own phone and just offer the service (SIM-Only). This still requires a one or two-year commitment in most cases.

The resulting spectrum assignment shows that even though there are relatively few MNOs that have obtained a license, each has only a small part of any given major frequency band (these are the 800-band, the 900-band and so on). This results in a need for whitespaces in the form of guard bands to make sure the different MNOs do not interfere with each other.

Another inefficiency of the current system has its roots in technology. Most of the spectrum is divided up into pairs because of the use of FDD, which also require guard bands to ensure sufficient QoS. The implications of this system is that the available PMC spectrum is used inefficiently.

3.2.3: Other means of spectrum access

Another method of entering the PMC market is to become an NVMO. These are parties that buy network services from MNOs at wholesale prices, and then sell these services on to consumers. This allowed for even more competition and lower prices during the course of the 21st century (Dunnewijk & Hultén, 2007).

The open spectrum is accessible to anyone. The reason no PMCs operate in these bands is the fact that they come with device restrictions. The EU, national governments and standards organizations set these limits (Council of the European Union, 2014a/b). They are in the order or magnitude of $10^{-2}$ Watts, where cell towers are in the $10^{1}$ range. This makes this part of the spectrum viable for private use cases with Wi-Fi being one of the most prevalent. Because
these devices have such a low power output, they don’t cause any significant interference in their geographical area.

3.2.4: Advantages and disadvantages of spectrum auctions
This command and control system clearly has a number of advantages. Parties are incentivized to become an MNO in the first place because of the exclusivity. It stimulates continued investments from the parties that win the auctions as well. When an MNO is guaranteed exclusive access to a certain frequency band, they are more likely to invest in proper infrastructure to profit of this access. Winners are a spectrum auction are likely to be parties that will utilize the given spectrum to the fullest extent.

Auctions also help a nation’s GDP because parties would invest if they obtain an exclusive license. The government will get an extra source of income every time there is an auction (Coarse, 1959). It also increases transparency compared to the government control model: it reduces the power that governments had over their spectrum (exclusively deciding who gets to use what parts). Economists also argue that the price a MNO will pay for the license will closely match the actual economic value of the part of the spectrum (Selian, 2001). Economic value is often interchanged with social value in the case of spectrum. This is because it’s nearly impossible to determine social or “actual value” of spectrum otherwise.

There are of course many downsides to this system as well. Because it’s such an intensive and lengthy process, the system can be seen as too rigid (Bauer, 2002b). Once spectrum has been allocated, it takes a while for new or updated networks to be operational and they will remain unchanged for a relatively long time. There are also the high investment costs to consider (Sutherland, 2007). These limit the potential number of parties interested in starting up a PMC network, which gives incumbents power. This leads to less competition at spectrum auctions, which in turn leads to lower prices paid to the people for the use of their spectrum. Fewer players trying to buy a license also means there is potential for collusion leading once again to lower paid prices to society for spectrum access.

Prices that are paid by the MNOs to obtain a license represent sunk costs from their own perspectives. This can lead to market players shifting their focus from providing a great service to recouping their investment costs as quickly as possible (Selian, 2001) (Bauer, 2002b). If all players provide mediocre service that cost a lot to the users, society losses in terms of total utility. Luckily, the fact that the market is open for NVMOs helps to keep prices reasonable for consumers. But the biggest reason that prices are what they are today is a result of regulation, mainly the monitoring done by NRAs (Dunnewijk & Hultén, 2007).

The biggest flaw with this system in combination with the current technologies is the underuse of spectrum. As said in the introduction, the majority of the favorable radio spectrum (300 MHz – 3000 MHz) is unused at any given time. Figures 11 and 12 give an overview for spectrum use in the 900 MHz – 3000 MHz range. The measurements were taken over a period of 24 hours at a typical location in the Netherlands. The x-axis represents the frequency in MHz and the y-axis the time of day. More importantly, the color represents the saturation in radio transmission in relation to a set threshold at a particular time in that particular frequency. This illustrates how spectrum is used: the PMC bands are heavily saturated, while many other parts of the frequency are barely used at all at a given time. As we will see in a later chapter, not all of the sparsely used spectrum can be used for PMC. There is a lot to be gained though, if both technology and policy were to be changed.
3.2.5: Upcoming changes in spectrum access and the spectrum market

There are some changes coming to spectrum access in the PMC space. Currently, there are huge roaming costs for users when traveling abroad, since spectrum markets are national markets. This has been the result of legislation regarding spectrum management (Stühmeier, 2012). MNOs face high investment costs to set up their network and therefore charge extra to facilitate roaming. There hasn’t been a strong policy regarding roaming charges since each country has their own national spectrum market. This can be seen as a failure of the original plan of the EU: they wanted a single European market to begin with when they started the GSM development (Agar, 2013).
The EU has been making moves towards one internal market for all PMC users, which will include the elimination of roaming costs (Council of the European Union, 2012b). Another big part of the RSPP is the harmonizing of spectrum throughout member countries. If countries have the same blocks in use for PMC, users can more easily roam on them, operators will have fewer complications and device manufactures will be able to provide cheaper devices. Finally, there has to be room for spectrum trading in these harmonized bands according to the EU. This is a frequency characteristic that market proponents have been arguing for since Coarse (1959), and puts more control in the hand of spectrum license holders or owners (Faulhaber & Farber, 2002). Trading can also be seen as a method to correct the sub-optimal outcomes of a spectrum auction, which has proven effective in the United States (FCC, 2013). The EU will not pursue a full market approach though: spectrum will remain available to license only and not become private property. Spectrum trading is another step towards a single spectrum market throughout the EU.

Is a spectrum market with auctions and trading necessary at all, when technology can make spectrum abundant or access more flexible? We’ve seen that the result of all this regulation and the command and control approach has led to under exploitation. This was especially the case with 3G spectrum auctions: they were very restricted and technology bound, leading to artificially high scarcity and non-competitive markets (Akalu, 2006). Many believe that the scarcity we current observe with spectrum is a result of old technology forcing this system of spectrum blocks (Ting, Wildman, & Bauer, 2005) (Akalu, 2006). The situation has somewhat been improved with the 4G auctions, but spectrum can still be utilized more efficiently. But simply opening up spectrum for use by anyone isn’t practical or desirable, as the next two chapters will show.

CR can deal with spectrum holes, whitespaces, and can facilitate spectrum sharing. A LSA model as set out by the RSPP may be the first step to solving spectrum shortages. The technology will soon be at a point that a new paradigm can be implemented that uses the spectrum more efficiently, and manages spectrum as a CPR more effectively. CR is designed to manage a large chunk of spectrum autonomously: there are fewer benefits if it must operate in the current system of spectrum blocks. CR can allow the spectrum assignment to become more transparent and would allow devices and base stations to manage this assignment. Fewer restrictions on spectrum access can lead to more innovation and a greater welfare for society (Werbach, 2003) (Ting et al., 2005).

3.3: Main points from this chapter
- After an initial period of “free for all spectrum access”, the command and control paradigm was implemented to manage interference in the PMC space.
- It was a good solution at the time and necessary because of technological limitations
- The current auction system does lead to a scattered spectrum assignment, inefficiencies, and spectrum holes,
- It also gives much power to the incumbent MNOs and leads to lower competition.
- There are alternatives that include a more market based approach or a more permissive commons based approach
- Current EU roadmaps take steps in the good direction by adding more PMC spectrum and suggestion things like LSA and CUS, but they still uphold the current command and control system.
- CR will not fully prosper under the command and control system and will need a more flexible spectrum assignment paradigm.
4: Theory: commons and common-pool resources

We’ve seen that in order to manage spectrum properly, governments had to turn towards regulating spectrum assignment. CR opens up the possibility of a new paradigm for radio spectrum. A natural assumption due to the self-governing nature of CR would be to make all useful radio spectrum accessible by everyone. However, the commons and common-pool resources in general aren’t without their own issues and a lot of work has been done to understand what they are and what one can do to manage them properly. This chapter will define the different types of public goods, commons, and the tragedy of the commons. Approaches to managing common-pool resources will be examined, as well as some theories regarding spectrum commons.

4.1: Public goods, commons and their tragedy

4.1.1: Public vs. private goods

Our society is based on the exchanging of goods and services between different parties. These goods and services are referred to as private goods, and their prices are mostly based on supply and demand. Regulation can influence their price in many different ways: restricting access, levying taxes, subsidizing production etc. But some goods aren’t traded at all and don’t have a price: public goods. These are free to use for all members of society and they often have a virtually infinite supply. This drives their price down to zero making it unattractive for private parties to produce or maintain them. Usually, a government takes the responsibility to produce these goods and services because this would be beneficial to the overall wellbeing of society. Some examples of such public goods are street lighting and public roads.

The main characteristic of a pure public good is that everybody can benefit from it, and the fact that one person using it doesn’t influence other people’s benefit. This leads to the definition that is used by most modern economics: goods are considered public goods if they are non-excludable and non-rivalrous (Varian, 1992). Of course, nothing is completely non-rivalrous since the world is not infinite. Public roads are considered public goods even if everyone using the same piece of road at the same time would lead to congestion. An important aspect of public goods is that they are not intrinsically public, but society has set them up that way because it’s the best way to manage the good.

Many goods and services are either non-rivalrous or non-excludable but not both at the same time. Non-rivalrous but excludable goods are often called club goods. An obvious example of this a membership of a golf club: someone being a member doesn’t have an effect on other people’s membership, but others can be excluded. Non-excludable but rivalrous goods are called common-pool resources (CPR). These are often vast natural resources that everyone can use, but they are not infinite. The fish in the oceans are a good example of this: anyone can go fishing, but there are only so many fish to catch. CPRs often have rules and regulations that surround them, for example fish quotas. Table 1 gives an overview of these different types of goods. These classifications are only a starting point. Practically all goods and services only loosely show these characteristics: breathable air isn’t technically non-rivalrous but it is considered a public good because of its abundance.
Most of the research done on CPR has been on traditional cases like fish and forests for example. There has been a growing interest for less conventional and obvious CPRs like radio spectrum (Hess, 2006). Even though broadcast television is a pure public good, PMC and Wi-Fi reveal the intrinsic CPR nature of radio spectrum when it is used for communications. You can’t technically exclude someone from using spectrum: anyone can set up a transmitter or receiver. But radio spectrum is considered rivalrous because there is interference when transmitting. The command and control system and device restrictions were put into place to limit spectrum use and thus prevent interference.

Spectrum is a special type of CPR because it is a natural resource that is instantly renewable. Typical CPRs can be depleted if used heavily like lumber, drinking water or agricultural viable land. Radio spectrum is infinite in the sense that it cannot be used up: transmitting information between 2.415 and 2.435 MHz does not render that band useless in the future. But it is used up in the time that information if being transmitted in that geographical area. They are unlike most other recourses: they are scarce locally but infinite overall.

4.1.2: Tragedy of the commons

“The commons” is an overall term for natural recourses that are freely accessible to the public. Every person has an equal interest in the good and everyone can influence decision-making surrounding it. It’s not a definition regarding the intrinsic properties of the good itself, but it’s about how a good it managed. How manages such a good in what fashion is also referred to as property rights (Ostrom, Burger, Field, Norgaard, Policansky, 1999), and will be discussed in the next section. Public goods can be considered part of the commons like for example general knowledge information: everyone can look up information about a wide range of topics. Private and club goods are never set up as commons. Their exclusive nature prevents that. Common-pool resources can be managed as part of the commons but also in various other ways.

Many CPRs do not belong to the commons and for good reason, namely because of the Tragedy of the Commons. This is a theory that describes inevitable negative results when a CPR is left open for use by everyone. It was described by Hardin in 1968 in what would become a very influential and heavily discussed paper (Hardin, 1968). At the time, the concepts of Adam Smith were very influential. The idea was that if each individual worked as hard as he or she could to maximize their own utility, the society would end up with the biggest possible benefits. This was known as the “invisible hand” metaphor. A logical conclusion of this idea was that individuals should have as much personal freedom as possible, in order to achieve that maximum utility for society.

Hardin stated that this was not the case for natural resources and he illustrated that with a simple example (Hardin, 1968). Imagine a field of grass on which everyone is free to roam around in or let their livestock live and eat. A couple of farmers decide to let their livestock graze in the field, of which they all benefit. One of them realizes that he can add to his livestock to increase his profits, in line with the thinking of Smith. After all, the grass is free to use by everyone. Others notice this and do the same. They keep adding livestock until the field is use beyond its capacity resulting in its destruction (disappearance of grass). Now, no one can benefit from the field at all. This problem manifests itself in all kinds of facets in our

<table>
<thead>
<tr>
<th>Non-excludable</th>
<th>Non-rivalrous</th>
<th>Public good</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excludable</td>
<td>Rivalrous</td>
<td>Common-pool resource</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Private good</td>
</tr>
</tbody>
</table>

Table 1: Different types of goods and services
lives, mainly with CPRs. Think of over population, air pollution, the fishing of oceans and rivers, or more local situations like free parking.

The Tragedy of the Commons occurs because people are free actors and often think rationally about what is best for them personally (Hardin, 1968). You cannot appeal to people’s conscience because they are too far removed from the eventual negative consequences. They are often aware of it, but don’t feel responsible for it since they are dealing with such a vast resource. The benefits of adding the extra cow (or equivalent in other scenarios) is very tangible so people will add that extra cow eventually. Harding stated that the only way to manage these CPRs is with mutual coercion even if that means giving up some personal freedoms (Hardin, 1968). All parties must come to an agreement about how much to take from the commons, as we cannot rely on people’s conscience to do the right thing. He famously gave overpopulation as an example: the people that follow their conscience and don’t have many children will have less descendants than those who do. Eventually, this conscience will die out and the Tragedy will occur in full swing again. But even in other cases: if you see everyone around you taking from and using the commons, you’ll be inclined to do the same. Rules must be placed before the tragedy occurs, or we are left with a metaphorical empty field. Regulating commons Harding argued, is not only better than not doing so, but necessary for the benefit of society.

As usual there was criticism to Hardin’s work and some of it is relevant for this research. One criticism was directed at the assumption that it was all about the number of people using a CPR (Gardiner, 2001). He stated that it was about the impact someone has on the commons, where Hardin focused more on the sheer number of users that take from the commons. If the impact of individuals could be reduced, more people could use the commons without the tragedy occurring. Gardiner also criticized Hardin’s assumption that people wouldn’t chose to keep that usage of a commons the same. He stated that individuals do make choices that look beyond the direct and short-term benefits, and they take reciprocity into account. This leads to the criticisms by Ostrom et al. (1999) regarding commons management. She claims that people can manage commons themselves without coercive rules and regulations. Her theory rests on commons being managed based on a set of rules that are agreed upon by all parties.: this will be discussed in the next section.

4.1.3: Spectrum and the tragedy of the commons
It’s been established that the radio spectrum that is used to transfer data is a CPR. Its corresponding tragedy manifests itself in the occurrence of interference: when there is too much of it, nobody can communicate. There are technical limitations to simply start using spectrum but without rules and regulations, useful radio spectrum will be used to near saturation. In the case of PMC, strong coercive regulations have been set up in the form of limitations to spectrum access, an auction system, and device restrictions. Spectrum for PMC borders the definitions of a CPR because of its nature, and a private good because of regulations. Wi-Fi that uses open spectrum bands can be viewed as a success example, but only because of the transmitter limits. The typical household does experience some interference because virtually anyone with an Internet connection is using Wi-Fi. Luckily, this interference is limited in most cases because of those transmitter limitations.

4.2: Common-pool resources and property rights
4.2.1: Property rights
Before you can develop any kind of management framework for you CPR, you need to clearly define the ownership of the resource. All resources in economics have a property right
attached to them. A property right is generally defined as: a socially enforced right to select uses of an economic good (Durlauf & Blume, 2008). Basically, it defines the ownership of the good: whom does this product belong to. Being allowed to use something exclusively is what ownership essentially is: when I own a car, I can use that car. But it also encompasses the possibility to transfer ownership (temporarily), to earn an income from the good, or in the case of resources: to let other people use the resource.

From this it follows that all property rights don’t have to be in the hands of one party: they can be divided between different people or groups. Think of a public park for example: the local municipality owns and maintains it, while everybody can use it. Private goods like the car don’t usually split their ownership and usage rights: both are in the hands of the person that owns the car. There are generally four different levels of rights that any given person or party can have in the area of CPRs (Bauer, 2002b). Starting from the lowest to the highest level they are as follows:

4) An authorized user only has limited rights to use and access a resource.
3) A claimant has management rights on top of that.
2) proprietors have all those right plus the right to decide if another party should be allowed to use the resource.
1) owners have all those rights plus the right to sell and/or lease their use.

4.2.2: Property rights of a common-pool resource

The definition of a common-pool resource doesn’t include a proper definition of property rights (Ostrom et al., 1999), as it only defines its rivalrous and non-excludable nature. CPRs can have different levels of property rights attached to them. This is usually determined on a situational basis by assessing how critical the resource or how scarce it is. Setting clear property rights is the first step to managing CPRs successfully. There are four main types of property rights suitable for a CPR as defined by Ostrom et al., (1999). They are illustrated in table 2, along with other names that are sometimes used.

<table>
<thead>
<tr>
<th>Open access</th>
<th>No enforced property rights</th>
</tr>
</thead>
<tbody>
<tr>
<td>Government property</td>
<td>Property rights held by a form of government (public property)</td>
</tr>
<tr>
<td>Group property</td>
<td>Property rights held by a group of users (common property)</td>
</tr>
<tr>
<td>Individual property</td>
<td>Property rights held by individuals or firms (common/private property)</td>
</tr>
</tbody>
</table>

Table 2: Property rights systems for common-pool resources (Ostrom et al., 1999)

Property rights in the area of CPRs can be counter-intuitive at first glance. They aren’t meant to make the resource fully excludable but they are there to put safeguards in place to prevent misuse or a tragedy of the common type situation. CPRs will appear as private goods to those that fall outside of its property rights, and as more public goods to insiders. Open access simply means the resource is without property rights: no one owns it, and everyone can use it. Think of breathable air or sunlight, no one owns those resources. Naturally, many more kinds of resources naturally fall under that category, but they’ve mostly been placed under government property. Government property speaks for itself: a level of government controls the resource and they may allow or restrict access to the resource. Since the government represents the people, this category is also referred to as public property by economists. If few or no restrictions to access apply, the resulting system is a resource that belongs to the commons. Take the public road example again: owned by the government, but anyone can use it. Different levels of government can be claimants or proprietors, but virtually everyone else will be an authorized user. Their limitations come in the form of speed limits, the kinds of vehicles you can use etc.
Group property and individual property systems are very similar and are sometimes referred to as a common property system. Both group and individual property rights place the control in the hands of individual people. They may determine how much of the resource may be consumed and by whom. The distinction between them is that in the case of individual property, users can easily transfer their ownership of the resource to another party, similar to a private property. In the case of group property users are more like proprietors instead of owners. Locally owned CPRs in the field of natural resources and ecological systems like a shared farm irrigation system belong in this category. The distinction between group/individual property and government property can also be used to distinguish the difference between a local and a more distant global authority (Ostrom et al., 1999). The different property right systems can be combined with different levels of property rights. The result is shown in table 3. There are slight variations of these categories in existence, which we will see in the case of radio spectrum in the next section.

<table>
<thead>
<tr>
<th>Open access</th>
<th>No levels of property rights</th>
</tr>
</thead>
<tbody>
<tr>
<td>Government property</td>
<td>A level of government is the owner, proprietor and claimant, most other people are authorized users</td>
</tr>
<tr>
<td>Group property</td>
<td>A level of government is the owner, and users are the proprietors, claimants, and authorized users</td>
</tr>
<tr>
<td>Individual property</td>
<td>A group of people has ownership, with a much larger group being the proprietors, claimants and authorized users. No government is typically involved.</td>
</tr>
</tbody>
</table>

Table 3: Property rights and different levels of ownership

Note that open access basically makes the resource part of the commons. The other three systems can belong to the commons depending on what the owners decide the rules are.

4.2.3: Managing a common-pool resource

These property rights are the basis for a management framework of a common-pool resource. None of the above systems is inherently better than the others: it strongly depends on the type of CPR (Ostrom, 2008). Property rights are set up to prevent CPRs from being over exploited (tragedy of the commons), and to create incentives for users to invest in the resource. The more owners and users are invested and have knowledge about the CPR, the better its exploitation will proceed (Ostrom, 1999). Ostrom set up a set design principles (criteria) that must be met in order to successfully manage a sustainable common-pool recourse (Ostrom, 1990). These weren’t developed with radio spectrum in mind obviously, but again they can provide a starting point. They are:

1. Clearly defined boundaries of the resource and their property rights.
2. Proportional equivalence between benefits and costs.
5. Clear sanctions.
6. Conflict-resolution mechanisms
7. The right to organize
8. Nested enterprises.

No. 1 relates back to property rights and the need to define them clearly. If property rights are clearly defined, owners can take better action against parties outside of these property rights and all parties that are involved are aware of their limitations. No. 2 states that a user of the resource must receive benefits that are equivalent to costs that they pay to use the resource. The distribution of the benefits and costs must be fair according to all parties, and must be
matched to the resource and local conditions. No. 3 relates to decision-making: everyone affected by the set rules must be involved in the decision-making process surrounding these rules. If they aren’t and parties see them as unfair, they are incentivized to break them because they can’t change them. No. 4, 5, and 6 speak for themselves: they all relate to rule enforcement. Monitoring and sanctions provide more incentive to not break any set rules. Conflicts will arise sooner or later, for which there must be a mechanism to resolve them. No. 7 is mostly applicable to more local CPR systems, where they are best governed according to Ostrom if users are allowed to organize on their own. In more global CPRs this principle simply suggests a right to organize for different actors. This will decrease the amount of times rules and regulations are challenged. And finally no. 8 says that governance should be nested: local levels inside more global levels. This will allow for a better diffusion of new rules and customs. Bigger levels can address the many smaller levels.

Not all of these rules will be perfectly applicable to every situation. They were meant as a starting point for CPR management, but every situation is different and every CPR is different. As a response to this, Ostrom introduced the concept of adaptive governance in the field of CPR (Ostrom, 2008). The meaning is implied within the words themselves: a form of governance for situations where the parameters surrounding a CPR change. It is therefore a more stripped down and general framework. Since spectrum is a relatively new and special type of CPR standardized solution may not yield optimal results. It is therefore worth it to examine these rules. Ostrom identified 5 requirements for proper adaptive governance:

1. Achieving accurate and relevant information.
2. Dealing with conflict.
3. Enhancing rule compliance.
4. Providing infrastructure.
5. Encourage adaptation and change.

No. 1 states that information about the resource and its users’ needs to be updated regularly. Many parameters like technology, user demands and availability of the resource, change constantly. All parties must be aware of as much information as possible, as soon as possible. No. 2 states that many CPR systems simply impose rules without any regard for dissatisfaction and conflict that can arise from this. Possible conflicts must be identified as soon as possible and resolved as soon as possible when they occur. No. 3 ties into this, and states that a CPR framework must encourage users to monitor themselves on top of existing monitoring mechanisms. It’s preferable for users to have a stake in complying with the set rules. No. 4 refers to an infrastructure that is well understood by the parties that need to use them and one that is flexible over time. No. 5 speaks for itself: the paradigm must encourage change to keep producing optimal results. Technologies and socio-economic arrangements change constantly and the management framework needs to adapt as well. Again, these requirements weren’t developed with radio spectrum in mind, but can provide a starting point for a new framework. This paper will use them as a test for a new PMC framework, to check if it manages spectrum as a CPR properly.

4.3: Managing spectrum, a common-pool resource

4.3.1: Economical and social value of spectrum

Lemstra, Groenewegen, Vries, Akalu (2015) considered the two points of view that are brought up and debated in the field of spectrum management. Their paper is about the trading of spectrum licenses, but their discussion can be applied here as well. The first view is by Coase, who directly contributed to the spectrum debate. In his view, spectrum management
should be concerned with efficiency and combatting interference. His approach would be to let governments clearly define property rights and let the market sort blocks of spectrum via trades. Again, this option seems most viable with current technological limitations, but is may but restrictive when it comes to CR. After all, Coase’s theories come from a time with analog transmissions only.

Another view relevant to spectrum is by J. Commons (Lemstra et al. 2015). He stated that any analysis should start with values that are held by relevant institutions and one should focus on how these are realized. So you should ask what the societal objectives are with regard to the use of radio spectrum. The actions of different actors in the field should be guided by one collective goal. Right now, society seems to value the use of spectrum to communicate reliably and provide benefits to our economy. This in combination with current technologies has led to the command and control system that is in use today. The result of this system is that it mostly evaluates spectrum in terms of economic value instead of its social value. It does address societal issues by enabling use of the spectrum in the first place, but the command and control system results in many restrictions for every day users. This may have been necessary up to this point because of technological constraints.

4.3.2: The social value of spectrum and spectrum infrastructure
Determining the social value of something like a good, service, or resource is hard in general. Frischmann (2012) talks about social value from the perspective of infrastructure. The networks that are setup by the MNOs and their corresponding services are the infrastructure needed to use radio spectrum. Frischmann stated that the problem is the focus on the supply-side: how much are people willing to pay determines how much infrastructure is constructed/supplied. Only what the market demands, and not what the society demands are “supplied with infrastructure”. Market demands and societal demands are not the same thing, even though they are often considered the same (Frischmann, 2012).

The focus needs to shift more toward the social value: all the commercial and non-commercial activities that infrastructure enables for both users and non-users (Frischmann, 2012). It can also be seen as societal demand: what the society as a whole would want from this infrastructure. It’s difficult to determine this demand precisely, because lots of benefits come in the form of positive spillovers and non-commercial benefits, and they are hard to quantify. But, society has to try and figure out the total of benefits as best as it can and focus on meeting the societal demand. The supply the amount of infrastructure must be based on social value that is generated in the future, not the money that is available today. Of course one obvious criticism is that the money is needed today, to build the infrastructure that is demanded tomorrow.

The current command and control system does exactly what Frischmann argues against: the infrastructure and services that are created are based on willingness to pay. They are also very restricted regarding who can access them and what they can be used for. With CR, spectrum can be managed more autonomously and a new paradigm can provide more value, both economically and socially. A less strict and non-exclusive spectrum paradigm may allow for more innovation in the wireless space: this can be considered both socially and economically valuable.

4.3.3: Spectrum and property rights
While spectrum isn’t often discussed in the area of common-pool resources, the idea of spectrum as part of the commons is not new. It has been thoroughly discussed in scientific papers for almost as long as it’s being used for communication. In the last decade this
discussion grew more prominent as the boundaries of spectrum and the current command and control approach became more apparent. Some people argued for more market based solutions and a move to a full market or ownership model, while other argued for an open access system. There are many other option that can be set up, which can have government or group property rights and variations on those regarding levels of ownership.

Coase’s 1959 paper on spectrum focused (for the first time) heavily on property rights as a method of understanding how the spectrum market could and should work (Coase, 1959). Spectrum is a resource that can be used, and people can be prohibited from using it using property rights. Well-defined property rights are seen as vital to manage a CPR in whatever way possible according to Ostrom and this is no different in the case of spectrum (Lemstra et al., 2015). Currently, people are the owners of the radio spectrum, but the government is representing them. Spectrum could therefore be called a government property, but it’s property rights are more split than the standard case from the previous section. The current system of command and control leaves the license holders as proprietors. They have the rights to manage the resource in the form of infrastructure: where they place their cell towers, what frequencies to deploy at what locations etc. On top of that, they can decide to exclude people that don’t have a contract with them. People that use a phone are generally considered authorized users: they pay their bills and they can use the spectrum to communicate based on that. Their usage rights are limited based on how much data they can transmit and what devices they can use to do so.

Changing from a command and control approach to a market approach as defined in Chapter 3 would make spectrum a private or individual property. Any party can buy a portion of it in a certain geographical area and become the owner. You could also grant more usage rights to the proprietors (MNOs) within the current command and control system in the form of spectrum trading. Instead of selling or buying the spectrum itself, you could buy or sell the license to the spectrum. There are steps taken to facilitate spectrum trading, as discussed in Chapter 3. Going the other direction: common property rights can be interpreted in two different ways. Spectrum could remain government property, with all users becoming claimants. This would leave some government control, as they get to decide if they want to exclude users for not complying with the set rules. Another option is to make spectrum a group property. A government, and therefore the people, would still be the owner but users would become proprietors. They can make much more decisions themselves about the set rules and matters like conflict resolution. This type of property rights is more suitable for local and smaller scale spectrum management, and for short-range applications.

4.3.4: Spectrum and the commons
The discussion that surrounds spectrum in a commons situation has largely taken place within the confines of current technologies. After most of the world had their first or second round of spectrum auction, people began to discuss the command and control approach vs. a market approach and vs. a commons approach. The market approach has been discussed in detail ever since Coase’s 1959 paper. It can handle the three objectives of spectrum management discussed in the previous chapter (allocation, assignment and adjustment) using market mechanisms. This is a more efficient system according to some due to competition, trading and bargaining (Matheson & Morris, 2012). Spectrum can be traded, but PMC spectrum can’t be traded as easily: an infrastructure is required to actually use the spectrum for long range communications. Only a few select parties with the means to build a nation spanning infrastructure could ever reasonably own PMC spectrum. The market approach has also been criticized for high transaction costs, the possibility of hoarding and the possible divergence that can occur in terms of spectrum bands and applications (Bauer, 2002b). High transaction
costs aren’t really an issue today: digital goods like advertising space or who owns what part of the spectrum of example can be traded fast and often in a given time frame. This will be used in the new spectrum management paradigm in Chapter 5. Hoarding spectrum can still be an issue, so a full market approach is most likely not the answer in the case of spectrum.

Spectrum as part of the commons has been discussed in the past as well. Its main criticism naturally has been the possibility to overuse spectrum, which leads to interference (Bauer, 2002. If users have no restrictions, they will end up interfering each other in a “Tragedy of the Commons” type situation. The main reoccurring conclusion in various papers is the need for technological improvement in order to remedy this interference (Bauer, 2002b) (Elsner & Weber, 2014) (Ard-Paru, 2010). The current technologies simply will not allow for an open access model because of interference and required infrastructure. The commons they do allow for and what many proponents seem to argue for is very restrictive and isn’t much different from the current command and control approach (Brito, 2006).

There have been proponents for a completely open common: Werbach proposed one example called the Supercommons (Werbach, 2003). He argued that spectrum is only scarce because of the assignment of frequency bands. This is shown in previous chapters to be to case to a certain extend. He proposed a system where the base rule is universal access to spectrum and that users would simply be held liable if they cause harmful interference. He denied the need for property rights in the area of spectrum, and argued that liability, device restrictions, and entrance based on technical standards would be sufficient. People would be naturally motivated to cooperate because of network effects. His views were mainly criticized for not being possible with current technologies (Ard-Paru, 2010). The liability and technical standards are a good start, but the lack of property rights leave the question of enforcement and conflict resolution unanswered. Spectrum is a CPR and clear property rights are very important in order to manage that properly. It also doesn’t prevent overuse that leads to interference, it combats it with liability law. It’s more efficient according to Ostrom to have clear rules beforehand.

4.3.5: CR and a new paradigm
There hasn’t been an opportunity to properly manage spectrum as part of the commons in the PMC space up until this point (Ryan, 2005). When discussing CR applications, most papers approach it like the licensed spectrum access model set by the EU’s RSPP: primary licensed users and secondary temporary users. (Badoi et al., 2011) (Tragos, Zeadally, Fragkiadakis & Siris, 2013). This is still relying on a command and control approach: a full commons based or market based CR system is rarely discussed. This is unfortunate since CR systems provide the most benefit in an environment where all radios are cognitive and able to access spectrum freely (Akalu, 2008). This can never be fully realized, because there will always be bands that need to be reserved for national interests like security and research & astronomy. This is reflected in other research, which concludes that a mix of systems is necessary (Bauer, 2002b) (Lemstra et al., 2015). Whatever system is chosen there will be huge switching costs due to the existing rules and routings, plus the need for new infrastructure. Property rights and the rules set by Ostrom for managing a CPR will be used in the next chapter to outline a new framework for managing spectrum.

4.4: Main points from this chapter
- Radio spectrum is a special kind of common-pool resource: it is local scarce but overall infinite.
- When left to open access, CPR will fall to the tragedy of the commons.
- Rules and regulations are almost always necessary to combat this, and this is not different with radio spectrum.
- Property rights are seen as the start of proper CPR management: the have different levels and can be spread among different parties.
- The frameworks by Ostrom can be used to set up and check CPR management paradigms.
- The current property rights and management paradigm are set up based on assumptions about technology, which are changed with the introduction of CPR.
- The current management paradigm does provide sufficiently in regard to market value but not in the regard of social value.
5: A new paradigm for personal mobile communications

As seen in the previous chapters, cognitive radio can’t be fully implemented in the current command and control system. It can be done to some extent (cognitive radio is about more than spectrum), but many of its benefits would be negated. This chapter will explore the what different elements are needed to build a new PMC paradigm and it will outline a new paradigm based on CR technology and a new way of doing spectrum management. The next chapter (Chapter 6) will outline the consequences of this new system in terms of policy, spectrum management and CPR management.

5.1: Building blocks of a new paradigm

5.1.1: Relevant actors

Various actors along with their goals and the things they value have been discussed throughout this paper. The first main actor is the national government. They value things like economic benefit, and a competitive communications market (Lemstra et al., 2015). To achieve this, they create the policies and rules the surround PMC, which makes them vital to changing the current paradigm. There needs to be an incentive that motivates a government to change its policies, like a solution for the spectrum shortage and an increase in economic and societal value that can be derived from spectrum. A new spectrum paradigm could also lead to more innovation and new wireless applications, which is in a government’s interest as well. As shown in Chapter 3, governments are also guided by rules set by standards agencies like the ITU and political unions like the EU. They do this because interoperability and collaboration provide benefits for all parties involved. All these parties also value innovation, since it leads to new uses of spectrum and therefore a greater benefit for society.

Another important group of actors are the MNOs. Most European MNOs are private parties, with only a small amount of being partly state-owned. They have sunk lots of money into obtaining licenses and building infrastructure. Like any private business they aim to maximize profits, which doesn’t necessarily lead to optimal results for society as a whole. Since the entry costs are so high, they are incentivized to provide a “good enough” service at least, or they risk losing customers and revenue. This can be considered market failure and governments try to correct this with spectrum policies and by giving authority to NRAs (See Chapter 3). Users get locked into multi-year contracts, further decreasing competition. MNOs are an important actor since they own the infrastructure and have relations with both device manufactures and customers, in addition to the government.

Device manufacturers have a relatively small role in the spectrum management area. Their job is to make sure that their devices comply with power restrictions and that they are fully interoperable with current standards. As said in Chapter 2, their devices need to be able to handle the technology or the whole paradigm cannot be implemented. They currently do not get involved in the spectrum management debate for the most part. They are mostly concerned with customer satisfaction and profits, as are MNOs for that matter.

Perhaps the most important actor is the end user, which includes virtually everyone in today’s society from the perspective of PMC. Everybody has a mobile phone and uses radio spectrum whether they think about it or not. They value all the benefits that PMC brings: fast, convenient and reliable communication whenever and wherever they want it. Typical users aren’t concerned with spectrum management in their everyday life. They are required to pay for the use of PMC infrastructure, and would like to see this price drop. Users would also
benefit from new wireless applications that benefit their everyday lives. A new paradigm that allows for more novel uses of spectrum would be appreciated by the end user. There are also parties that use radio spectrum for other purposes than PMC the two most notable being national defense and research institutions (Astronomy for example). They value things like accuracy in the case of research and private reliable communications in the case of defense. This has led to the allocation of exclusive spectrum for those purposes.

What this illustrates is that the current situation has two sides: what the government and users value on one side, and what the MNOs value on the other. Economic and societal value vs. economic value alone (for the most part). MNOs can be seen as a means to an end: we need to access and use spectrum so we’ll have to deal with relatively high prices that the MNOs charge. Users typically pay a lot because of the investments made by MNOs in terms acquiring spectrum and building the infrastructure. Multi-year contracts and the fact that relatively few MNOs operate in each country further increases the costs for users. In the past, the command and control system was the only option to combat interference effectively. It should have gone even further according to market proponents, with MNOs being able to outright own spectrum. The introduction of a new paradigm provides a unique opportunity to re-evaluate things, and use the new CR-based technologies to tip the scale more towards societies values and goals.

5.1.2: Spectrum allocation vs. assignment
There are a lot of elements in the field of spectrum management that need to be considered. First, there will be a transition period no matter what you change. Spectrum management has remained relatively unchanged since the start of GSM networks in the early 90s. There have been many investments in infrastructure, rules, routines, and devices over the years. This makes the whole ecosystem highly resistant to change, making regulatory intervention necessary for CR to take hold. A lot of testing will be necessary as well. The technology is still under heavy development causing uncertainties about the future.

Next is the allocation of spectrum: what spectrum to use for PMC. Even though CR systems will use the spectrum that is available more efficiently, it also provides an opportunity to use new spectrum bands for PMC. The most desirable spectrum is in the 300 MHz to 3000 MHz range. Some of those bands are used for astronomy/research purposes, military applications or are open spectrum. Wi-Fi is another interesting case: it works with today’s technologies because of strict transmission limits. Wi-Fi could be excluded from a CR system or you could let a CR system work around those transmissions automatically. It can also be integrated over time into the PMC space, something that’ll be discussed in the next sections. Note again that the allocation of spectrum refers to which part of the spectrum is used for what application. The assignment of spectrum refers to using a particular central frequency and bandwidth for a given application.

5.1.3: Spectrum access and pricing
Current spectrum band prices are largely based upon the scarcity of spectrum in combination with current technologies and current spectrum management. PMC based spectrum access also requires infrastructure. No matter what technology lays underneath, infrastructure costs a lot to build and maintain. It is vital for any form of communication to work. This cost has always been covered by the MNOs in exchange for exclusive spectrum access and revenue appropriation. As discussed in Chapter 2, CR can decrease the price of spectrum, and drive the operational costs of a PMC network down. Exclusive spectrum access will not be applicable in a CR based paradigm, so it comes down to appropriation of revenue. What amount of money is paid for spectrum access, to which party are they paid, and by whom are
they paid? Transaction costs have also been relevant to spectrum, especially in the case of spectrum trading. These are the costs that arise want transferring spectrum access to a certain band from one party to another. Transaction costs are trending downwards in a CR system as well: it all comes down to infrastructure and local scarcity of (long-range) spectrum.

5.1.4: Regulations
Chapter 3 explored the current state of spectrum management and regulations. Every spectrum management paradigm has to have some regulations associated with it. Even though CR systems can technologically regulate themselves to a certain extent, there is always the possibility of interference or abuse. A system could be manually programmed or exceed transmitter limits for example. A national government has traditionally made the rules and regulations surrounding spectrum, based on input from parties like the EU and ITU. A CR based system requires a large amount of cooperation, regulation, and oversight (in the form of an NRA for example). The main goal of regulations in this is to make the new paradigm possible. The technology allows for many new possibilities, so the new regulations should facilitate this.

Rules and regulations can be used as a tool to consolidate power with different actors. Where this power is concentrated will always be a point of contention (Akalu, 2008). Vested interests in the command and control paradigm, like MNOs, will likely push to keep the status quo. They not only own the infrastructure but have exclusive spectrum access rights. CR systems will make spectrum bands cheaper and will require exclusive spectrum access to be abolished. New rules and regulations will have to find new roles for all actors, including a new power balance.

5.2: Device Controlled Frequency Access
The new paradigm revolving around CR and spectrum access will be based around devices and infrastructure instead of spectrum licenses. This traditional way of spectrum management follows a mostly top-down approach: policy is set at a high level, and decisions about frequency use are made at the high level. The new system will still follow rules set at the top, but these rules will allow for a more bottom-up approach in terms of spectrum use. More decisions will be made at the device level, in real time, and by technology. This will help to better utilize of radio spectrum and will allow PMC spectrum to be used in novel ways. It is a new way to manage spectrum and it will be called Device Controlled Frequency Access (DCFA). This name describes the core of the new paradigm: devices, not regulation, will handle frequency assignment.

5.2.1: Spectrum assignment with CR in DCFA
With DCFA, PMC spectrum bands will ultimately disappear and all spectrum will be available to all carriers and users. Spectrum allocation will still be something that will be determined beforehand and on a macro level (see Section 5.2.3). But with DCFA, spectrum assignment will be transferred to a more local level. As discussed, CR systems will allow for communications to adapt to its surroundings when choosing parameters like central frequency, bandwidth, and transmit power. This will require the device that people use to become “smart” in the area of spectrum assignment. Instead of policy dictating what specific parts of the spectrum are used at a given time and place, the device and base stations can now do it based on its spectrum sensing input. As described in Chapter 2, the base stations and phone will set their parameters (central frequency, bandwidth, power etc.) based on input from the RF environment. This can happen automatically and the system’s ability to provide proper QoS will improve over time.
This system could either be implemented centralized or distributed. Busy sections, like cities, could greatly benefit from a centralized system. Lots of users will want to access spectrum at the same time, so a powerful centralized decision-making server can provide optimal throughput and learning capabilities. How much area each of those servers must cover, will again be answered by testing. More rural areas will not have a need for such optimization. However, centralization provides other benefits in terms of billing, which will be discussed in a later section. The system will also be cooperative to yield optimal overall configurations: it’s all about using the available spectrum as a whole more effectively.

The rest of the technical implementation of this system is beyond the scope of this paper. There have been steps towards a “5G” PMC technology definition that can provide the air interface and the backbone for DCFA. As of today, these proposals are still based upon spectrum bands and the command and controls system. DCFA could technically be a LTE based system with added CR capabilities, but a new generation of technology is a natural opportunity to improve the air interface. Base stations will most likely be easy to upgrade: components can be big and there aren’t any practical power limitations. Devices will offer a bigger challenge. Spectrum sensing will have to be added to the current devices that people use today. Luckily, technology is still becoming more advanced and mobile phones are still moving forward. If a centralized system is used, more functionality can be offloaded from the device and the device will have to use less of its sensing and decision-making capabilities. Over time, other devices ranging from wearables to cars could be set-up to use the PMC network in the DCFA paradigm. But for the rest of this papers, phones will be used as the main example.

The biggest difference between this new paradigm and the existing paradigms that are often discussed in papers surrounding CR is the absence of primary and secondary users. CR has largely been discussed as a measure to fill spectrum holes, but a full CR based PMC system has been relatively unexplored. There may still be parts spectrum that are “off limits”, or parts that need a primary/secondary user approach either as a transition or indefinitely. This will be discussed in the next two sections. In DCFA every user starts as an equal. Less top-down style management will be required to use PMC spectrum efficiently: CR technologies allow for true spectrum sharing in the PMC space for the first time ever. Whitespaces that are set up between different license holders will become a thing of the past, and situational spectrum holes due to local underutilization can be used by other users as soon as they need it.

5.2.2: Transitioning to DCFA
A server that is present in a base station in combination with input from user devices will make some of the decisions that policy used to make. This will require a whole new generation of mobile devices and base station infrastructure. One obvious option is to go with an all IP infrastructure just like LTE was implemented. VoIP has surpassed traditional circuit switched calls in terms of quality, and SMS services are being replaced rapidly with over the top messaging services like WhatsApp. Today, this requires third parties but this doesn’t always have to be the case. VoLTE is being deployed worldwide today and an IP-based messaging service that will be integrated into DCFA can always be developed. A full IP-based infrastructure would benefit from a TDD interface, which will be discussed in the next section.

No matter what options will be chosen, there will be a significant transition period. This will require investment from governments to facilitate this change, MNOs to upgrade their infrastructure, and the device manufacturers to add sensing capabilities to their device. Even the end user is required to invest in the form of buying a new device. This user investment is
acceptable since phones are usually upgraded every 2 to 4 years. The investments by the other parties will pay off in terms of reaching the goals set for future spectrum use, and by being able to derive more value from the available spectrum. The MNO may not want to transition for reasons that will become apparent in Section 5.3. But the transition can be considered necessary in order to keep increasing the use of radio spectrum, which has is currently happening and will continue to happen for the foreseeable future.

The new system will have to work with current emergency call requirements. These could be given their own frequency block or they could simply take priority over all other traffic in the local network. This is already done within a MNO’s frequency band today: when a user calls an emergency service, that call will be prioritized above all other traffic. Phones will have to be replaced too. The new phones could be developed to work with both current and the new CR technology during the transition phase. A better option would be to operate the base stations in a “dual mode” during the transition. Phones support three generations of technologies today, namely 2, 3, and 4G networking. Once VoLTE has been rolled out, newer phones will only have to support LTE. DCFA can be added later, and eventually LTE can be phased out.

5.2.3: Spectrum allocation for DCFA
The next spectrum paradigm is still bound by the laws of physics: it needs a certain amount of bandwidth to order to operate. The implementation of DCFA provides an opportunity to take inventory of current spectrum allocations and not only create one PMC spectrum pool, but also add more spectrum for PMC. The current spectrum allocations can be used as an obvious starting point. The main focus will be on the 300 MHz – 3 GHz section of the spectrum, generally called the Ultra High Frequency (UHF) band. This is considered the most desirable band for PMC. Each country within the EU has slight variations in their spectrum allocations so the Netherlands will be used by this paper as an example.

Werbach (2003) argued that spectrum bands don’t exist, and that they are man-made constructs. He argued that spectrum should be seen as one big pool and that no agreements on what frequency should be used for what application are necessary (as long as you don’t interfere one another). However, this argument fails to see that some applications require specific frequency bands to operate. They also completely negate the notion of property rights and CPR management. A big pool of PMC spectrum will be defined for use in DCFA.

Naturally, there is a big section of the UHF spectrum already allocated to PMC. All of this spectrum could be used in the new DCFA paradigm without issues. Currently there is about 590 MHz of bandwidth licensed to MNOs in the Netherlands. This includes the 800 MHz band (791-862), the 900 MHz band (880-960), and the 1800 MHz band (1710-1880), the 2100 MHz band (1920-2170), and the 2600 MHz band (2500-2690) (Agentschap Telecom, 2016). There is an expansion planned for the 2100 MHz band that will take effect in 2017 (Agentschap Telecom, 2016) and the 700 MHz band will most likely be available in 2020 (Lamy, 2014). The spectrum is divided up among the different MNOs (four in the case of the Netherlands). Most of it also has gaps within them that are assigned to applications like national defense, reserved for astronomy, or are open spectrum. An overview of the current available PMC spectrum is given in table 4 (all units are in MHz). The total amount of frequency currently in reserved for PMC in the near future is 710 MHz of bandwidth.
<table>
<thead>
<tr>
<th>Band (MHz)</th>
<th>Uplink freq. (MHz)</th>
<th>Downlink freq. (MHz)</th>
<th>Total freq. per band (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>700 (planned from 2020 onwards)</td>
<td>N.A.</td>
<td>N.A.</td>
<td>90</td>
</tr>
<tr>
<td>800</td>
<td>832-862</td>
<td>791-821</td>
<td>60</td>
</tr>
<tr>
<td>900</td>
<td>880-915</td>
<td>925-960</td>
<td>70</td>
</tr>
<tr>
<td>1800</td>
<td>1805-1880</td>
<td>1710-1785</td>
<td>150</td>
</tr>
<tr>
<td>2100</td>
<td>1920-1980</td>
<td>2110-2170</td>
<td>120</td>
</tr>
<tr>
<td>2100 (expansion from 2017 on)</td>
<td>1900-1915</td>
<td>2010-2025</td>
<td>30</td>
</tr>
<tr>
<td>2600 (paired)</td>
<td>2500-2065</td>
<td>2620-2685</td>
<td>130</td>
</tr>
<tr>
<td>2600 (unpaired)</td>
<td>N.A.</td>
<td>N.A.</td>
<td>60</td>
</tr>
</tbody>
</table>

Table 4: Current and planned spectrum allocations for PMC in the Netherlands

An important thing to note is that this spectrum is being used for three different generations of technology (2/3/4G), further decreasing the throughput that can be achieved. On top of that frequency bands are split into an uplink and downlink band. This is a result of the wide implementation of FDD based transmissions. One option for DCFA is to use a TDD based air interface to use PMC spectrum more efficiently. CR may be able to combat the interference that is inherit to TDD systems. CR systems are aware of their environment after all, and could learn what the best times are to transmit and receive data. TDD also makes more sense in an all IP network. Users typically benefit from a higher download speed than a higher upload speed: TDD can divide the spectrum up as is necessary in a given situation. There is still a technically debate going on about the merits of a TDD based air interface. It is too early to definitively say TDD can be used in this new system.

All of radio spectrum currently reserved for PMC can become the pool that users can use to connect to the network. Because of CR, this spectrum will be used far more efficiently than it ever could have been in the past. Unfortunately, there is little actual data on how much data throughput can be improved. This will require further research and more testing. But looking at temporary spectrum holes and whitespaces alone, DCFA will provide significant benefit. The PMC spectrum will not need specific bands anymore: the whole section will become one sharable pool. The learning capabilities of a CR network will increase the benefits of DCFA even further. All spectrum can be used for the newest technology, since there will not be a need to fall back on older generations of PMC. This satisfies a spectrum management requirement set by Bauer (2002b) to adapt internally to new technologies.

To adapt externally, i.e. adding more spectrum, we have to look at parts of the spectrum that are used for other purposes. The addition of the 700 MHz band and the expansion of the 2100 MHz band fall in line with this. Anything below 700 MHz has been reserved for television and radio broadcasting for the foreseeable future (Lamy, 2014). Spectrum in between 900 and 1700 MHz and in between 2500 and 3000 MHz has been largely reserved for applications such as radio astronomy, satellite communications, GPS, and radar (ITU, 2010a) (Agentschap Telecom, 2016). Radio astronomy is a subfield of astronomy that uses radio signal at a variety of frequencies to study celestial objects. There is a host of specific radio frequencies in the UHF band that can be used to study the presence of certain elements. These frequency bands need to be free from all possible interference to do this properly. They also need a relatively wide margin due to Doppler shifts caused by movement between the observer and source (ITU, 2010a). The ITU recommends that the frequency space surrounding these bands are kept free from other activity as much as possible (ITU, 2010b). It is therefore a better solution to keep this part of the spectrum out of the PMC pool. This can always be evaluated again in
the far future. Other frequencies in that area are used for other high range, sensitive applications like radar and GPS.

There is open and unlicensed spectrum to be found “in between” the current PMC bands, often in between the uplink and downlink frequencies. They include in the 821-831 MHz, 1785-1805 MHz, 1880-1900 MHz, and 2300-2400 MHz bands. These bands could be used in the DCFA paradigm: CR can self-configure when another application is using the spectrum. Having a larger continuous pool without interruptions will help the CR system to pick more combinations of power, central frequency and bandwidth. This can’t be done without risk of interfering with current uses of those open bands. Tests will have to be conducted to see if this becomes an issue in practice. Use cases of that open spectrum are low-range devices like wireless microphones for example. If this does prove to be problematic, DCFA could always be set up like a secondary user in these bands.

Some of the spectrum “in between” the PMC spectrum has been allocated to military purposes. Examples are 915-925 MHz, 1785-1805 MHz, 2025-2110 MHz, and 2200-2320 MHz bands. Note that some of this is already shared with the open spectrum. Adding this spectrum to the PMC pool would be greatly beneficial, but military applications have high standards of security and reliability. However, part of the current spectrum already overlaps with open spectrum and on top of that, transmissions can be securely encrypted. Research has called military applications as an application of CR technology because of its flexibility (Akyildiz et al., 2006).

The final part of the spectrum to discuss in this paper is the 2.4 GHz band, also known as the industrial, scientific and medical (ISM) band. It ranges from 2.4 GHz to 2.5 GHz and it was originally set aside for non-communication applications. Because it has been license free for a relatively long time, it’s used for many different communication purposes. One of the biggest applications is Wi-Fi. The band can be very saturated at residential locations because of the big number of Wi-Fi base stations. There have been studies that examined the possibility of PMC application co-existing in these bands but they have mainly focused on the 5 GHz bands. One study for example showed that Wi-Fi and LTE could coexist in the 5 GHz spectrum, because they have different cyclical properties (Syrjälä & Valkama, 2015). One option would be to make Wi-Fi base stations CR based as well: many Wi-Fi routers change their channel already based on input from the RF environment. This may prove sufficient and makes it possible to add this band to the PMC pool, but extensive testing will be necessary.

All of this extra spectrum can transform large parts of the UHF band (700-960 MHz and 1710-2400 MHz) into one big spectrum pool that a DCFA system can use. This will not be enough to meet the set goals like the 1200 MHz goal but it is still an effective way to increase the throughput of PMC system. DCFA will allow the available spectrum that is currently in use for PMC to be used more efficiently. The soon to be added 700 MHz band and the expansion of the 2100 MHz bands can be used for testing since they are not in use for PMC today. The 700 MHz band is especially suited for this because of its relatively long propagation (this a property of the lower parts of the radio spectrum). A relatively large area can be tested with relatively few base stations.

5.2.4: New applications of DCFA spectrum

No matter how smart a CR system becomes, Shannon’s channel capacity still applies. This is evident in the open 2.4 GHz or ISM band: many applications use this open band and its characterized with high amounts of interference. The amount of Wi-Fi networks alone causes problems, and there are many other applications operating in this band like Bluetooth,
cordless phones, baby monitors and so on. Still, all of these applications have been developed in relatively constrained spectrum bands.

With DCFA, spectrum will not be exclusively licensed to a third party anymore. Because the main PMC system will be cognitive, the whole spectrum pool can be opened up for short range applications. The main limitation will be that long range applications will be for PMC transmission by an MNO. But for the first time, PMC spectrum can be used similarly to the ISM band and other open spectrum bands today. CR technology can work “around” the long-range PMC transmissions but this will require testing. Opening up the PMC spectrum to short-range transmissions will allow for the development of new applications, which are no longer restricted to a small section of the radio spectrum. There could be a growth in innovation because of this. There will even be less interference and more benefit overall if these new short-range applications also use cognitive radio technologies.

5.3: Paying for spectrum and infrastructure access in DCFA

5.3.1: The current situation for users and MNOs
Users pay their monthly bill to an MNO to use the infrastructure that can make use of radio spectrum to send and receive data. They usually engage in a multi-year contract where they agree to pay a certain price each month to get a certain amount of call time and a certain amount of data. The pricing structure is relatively simple: the more data you use, the more you pay each month. Users often aren’t aware what the price is actually made up off: infrastructure, spectrum auctions and profit. MNOs take money in exchange for letting users transmit data using their infrastructure. That revenue is split up into infrastructure costs, spectrum license costs, other costs and profits. Naturally, this is simplified version of the costs structure. The infrastructure is build up and maintained by a MNO themselves. As seen in Chapter 3, the price of a spectrum is determined by a spectrum auction.

5.3.2: Becoming an MNO in DCFA
As is the case with the technical implications, a lot of previous research regarding the price or value of spectrum focuses on spectrum holes and primary vs. secondary users (Tragos et al., 2013). DCFA provides an opportunity to restructure MNOs. From the perspective of an MNO, radio spectrum will not have a traditional price anymore. There is one big pool of PMC spectrum now. Users are connected to the base station on parts of the spectrum that are chosen by the CR system itself.

There has to be some barrier to entry for long range transmissions to prevent unnecessary interference, so becoming an MNO should still have some requirements. These can be a form of payment to the national government, a contract in which the MNO agrees to meet certain goals at certain times, or a combination thereof. MNOs will not license a spectrum band anymore, but they can simply obtain a license from a national government to become an MNO. Once a party has become an MNO, they set up an infrastructure and they can receive payments from users that use their network as usual. Users will not want to sign a contract with a smaller or local MNO that only services a relatively small area: the payment model will have to change as well.

MNO’s will not have the big up-front costs anymore. This will also allow for more infrastructure to be built by an MNO and it can even result in more and easier competition on the local loop. The lower barrier to entry has another benefit: smaller parties can become their own local MNO. The MNOs that users sign a contract with almost always exist on the national level. On top of that, many are owned by multinationals making them part of a global
company. With DCFA, smaller MNOs will not have to license spectrum anymore, making it much more viable to become one. Smaller or community based MNOs can be set up to provide service to more remote and rural areas. These are often left with an infrastructure that is too sparse because it is not economically viable to provide service to a large and low populated area. Going in the opposite direction: users in busy city centers sometimes have trouble getting decent service, especially during rush hour. A local MNO get be set up there as well, to provide a high concentration of base stations.

DCFA will break the contract model, and break the tie between the user and one particular MNO. Spectrum is now one big pool that all the MNOs share, and users will essentially become the same: hopping between MNOs based on transmission parameters like interference. To facilitate this a new payment model will be introduced.

5.3.3: Spectrum supply and demand
DCFA will introduce variation in the price that users have to pay to an MNO based on supply and demand. No matter how good a CR based base station is, there will always be some level of interference. Access can be priced based on spectrum supply and demand at a location during a specific time frame. The system knows how many users are connected to the same base station, or how saturated spectrum use is in an area in general. Busy cities will deal with heavy saturation so it makes sense that users pay more if they operate in a “busy” part of the spectrum: it’ll be more difficult to offer similar QoS in that case.

Remember that spectrum usage will only increase as time goes on, especially if more and more devices and appliances become wireless and more applications are allowed in the PMC spectrum. So instead of users paying a monthly fee, they buy access to infrastructure when they need it and where they need it. As we will see in the next chapter, this corresponds with the recommendations on how to manage a CPR better than the current system does. It does raise some important questions however, like: how will the price of access be determined and what is relationship between the MNO and the user?

5.3.4: Real-time bidding
Your phone typically has a connection to the base station in case you receive a call, text message, or data. This is a baseline that is always there and always on. It is necessary for mobile devices to function in the way that we expect. This baseline can change frequencies when necessary with a CR-based system, but it’s always on and users aren’t charged for it. This is possible since it can be set to relatively small bandwidth. The rest of user interaction with the phone happens in bursts: you browse the web, you answer a call etc., before you put your phone back in your pocket. This is the moment in which users require a lot of data in a relatively short time.

DCFA will allow users to buy access to infrastructure on a session basis. Prices can be re-determined each time a user initiates a new session. This price can depend on the current interference temperature, number of users in an area, number of users connected to a particular base-station, strength of the connection, and various other statistics. Because the system is cognitive and engages in learning, more and more predictions can be made on how much data this user is going to consume and how the interference temperature will change in a given time frame. All of these variables can be used by central servers within a very small time frame, similar to real-time bidding in the advertising world. Real-time bidding is used more and more to sell advertising on a per instance basis (Yuan, Abidin, Sloan, & Wang, 2012). Every time a user visits a webpage with a location for an ad, a third intermediate party receives a request for an advertisement. A host of advertising companies can bid to show their
Instead of paying the highest price (something you think of when thinking about auctions), the real-time bidding system is used to determine the lowest possible price for spectrum access. MNOs can automatically engage in a mini-supply auction every time a user wakes his or her device from sleep or stand-by mode. People that use spectrum in congested areas will most likely pay a little more than people that use spectrum in areas with lots of free spectrum. Overall, the amount of money a user pays each month will be lower compared to the current situation due to the big pool of available PMC spectrum and the efficiencies of a CR based system. The price that is determined will be the current price per unit of data for that given session. If a user’s parameters aren’t expected to change, MNOs could also offer multiple sessions for the same price. On the other hand, when a user hasn’t woken his or her phone but parameters change, real-time bidding may be used to find a more suitable connection.

All of this happens transparently and automatically from the point of view from the user. This is great in the sense that the user doesn’t have to think about it: one of the benefits of a CR-based system. Because users still have to pay, they should be able to have some control over this and set some of the parameters themselves. They could chose to go with the cheapest possible connection all the time, given them the greatest monetary value. Or they could want the best connection all the time, making sure they can send and receive data as fast as possible. How much control is necessary and what parameters a user will be able to control will have to be determined by testing.

5.3.5: The future of MNOs and their relationship with users
One consequence of the real-time bidding system is that users can and will use different MNOs in different situations. This changes the relation between the MNO and the user. Users typically have a one- or two-year contract with one MNO that includes a subsidized phone. With DCFA, people will have to pay for the full price. It will be a bigger up front cost for users, since they are for the most part used to buying a phone that is subsidized. But buying a phone outright instead of subsidizing it is not new. Customers have always had the option of buying a pre-paid sim of sim-only contract and extend the lifetime of their devices. Contracts will not be relevant or applicable anymore in with DCFA and real-time bidding. Exclusive spectrum rights through auction and cell-phone contracts essentially give MNOs much ownership and control over radio spectrum. The phone you buy will include a basic connection to any MNO for listening and for emergency services. Since this connection will be free to use, it doesn’t matter which MNO is used. The one with the best connection to the user will serve the connection, until parameters change and a better option will be made available. The phone must also retain a SIM-card or a similar technology that offers a unique identifier tied to the user. This identifier can be used for the real-time bidding, and billing the user.

Since users can connect to different MNOs in different situations, billing them will be different than before. There has to be a third party, similar to the advertisement situation that handles the auction. This will be called the Intermediate for the purpose of this paper. The Intermediate initiates the auction when the user unlocks their phone or when parameters change. An auction could also be initiated when a MNO has a better offer for the user. The Intermediate can be notified that an auction is necessary via the basic connection that is
always present. The Intermediate can also keep track of data usage and bill the users on a monthly basis. This money can be distributed to the MNOs based on the percentage of total data transfers they’ve initiated. It’s up for debate whether the Intermediate will be a private company or a government run entity. Both will have their advantages and disadvantages in terms of efficiency, privacy, etc. Whatever option is chosen, the technical implementation can simply be a software layer that is present on phones and base stations, similar to the advertisement situation. This software benefits from the learning capabilities of CR technology.

This payment structure forces the MNOs to become less visible to the consumer: they become a provider of spectrum access infrastructure. Consumers will not have a need for a contract anymore or even be exposed the MNOs branding. Today, many MNOs try to lock customers in by using contracts, by providing add-on services like a music streaming subscriptions, and giving them all sorts of apparent benefits. All those added services also cost the MNO money, making the monthly bill more expensive for users. Customers will most likely be better off with MNOs being a “dumb pipe” and adhering things like net neutrality. When an MNO can advertise to the user, they are incentivized into making “zero-rating” deals with certain service providers or with their own services. A zero-rating deal allows the user to transmit data to use a particular service without charging for that data. This stifles competition, because no user would want to use a competing service that costs them money to use.

With DCFA, MNOs become more like a basic utility, with their only concern being the transmission of data as fast and cheap as possible. MNOs will still have an incentive to provide good QoS since a lack thereof will exclude them from the bidding process or cost them their MNO license. It’s likely that overall QoS will improve since consumers aren’t locked in for a two-year period anymore. This will incentivize MNOs to provide a proper infrastructure and QoS at all times to compare favorable to other MNOs in the auction process. This will lead to a better utilization of radio spectrum in the long term. Lower barriers to becoming an MNO may further increase QoS through increased competition. It’ll all just happen without the users being aware of it.

5.4: Main points from this chapter
- A new paradigm called Device Controlled Frequency Access will be implemented to facilitate a cognitive next generation PMC system.
- DCFA can automate spectrum assignment on a per use-case basis.
- The PMC spectrum will be made into a pool that will be as big as technically possible.
- Because of the cognitive nature of DCFA, there will be more short-range applications allowed in the PMC pool.
- A real time bidding system will be implemented to ensure that users pay the best prices for access to infrastructure. Users will be able to switch MNOs easily.
- An party called the Intermediate will facilitate these auctions and bill the users automatically through software.
6: Evaluating DCFA

Now that DCFA has been defined, this section will give an overview of the new paradigm and examine it in more detail. DCFA will be examined through the lens of spectrum management, and property rights. It will also be tested using the theories by Ostrom, to examine if DCFA manages radio spectrum properly from the point of view of common-pool resources.

6.1: DCFA and spectrum management

6.1.1: Overview of DCFA

DCFA is a new paradigm and a new approach to spectrum management, partly made possible by technological advancements. One big pool of PMC spectrum has been defined, which all MNOs will share using CR technologies. As discussed in Chapter 2, CR-based networks can provide service with sufficient QoS automatically and they get better over time. A party can become an MNO and build an infrastructure. All of the PMC spectrum could potentially be opened up for short range applications. This will have to be tested of course, but the general public can make use of a significantly bigger portion of the radio spectrum for different applications. Those wouldn’t have to be CR-based at first, but could become so over time. The addition of CR to long-range PMC transmissions also allow for more applications to use the PMC networks.

The price of access to the infrastructure for a given situation is determined by a real-time bidding every time the user unlocks his or her device. If another MNO can offer the same QoS for a lower price, or a better for the same one, a device can automatically be moved over to the “winning” MNO. This most likely will not result in a change of MNO all the time: if no parameters change significantly, no change of MNO is necessary. But as parameters like time of day or location change, other options might be more beneficial for the consumer.

The following figures (figure 13 and 14) will give a more visual overview of the workings of DCFA in a typical scenario. Figure 13 relates to the technical working of DCFA. It shows a user connected to an MNO’s base station (1). They receiver service as usual but over time, more users may come into the area (2). They cause an increase in interference and all devices send their data that they gather from their spectrum sensing capabilities. After a certain point the CR system determines that it can no longer provide adequate service anymore. It sends a signal to the user’s device (3) with information about the new transmission parameters, and the connection gets moved over to a new central frequency and bandwidth. Another user (4) might experience interference from a group of short range devices operating between the user and base station. Again, based on past and current data that is sent from the user to the MNO, transmission parameters can be changed to work around this.

Figure 14 shows the payment side of DCFA. A user has a connection with a MNO (1). At a certain time, parameters change: the user moves into a new area, wakes up their device etc. This is passed through to the Intermediate (2), and the other MNOs are notified and checked if they have a better offer. This can be a better price per data unit, or a better QoS for the same price. If more than one MNO has an offer the winner will be determined by a real time-bidding. If another MNO wins (3), the user’s device is notified of the new connection parameters via the existing connection. The device than connects to the new MNO (4).
DCFA restructures the way spectrum is managed and owned by the various relevant actors. The old system was set up to deal with the shortcomings of past and current technologies. It worked, but it was slow to adapt and left radio spectrum underutilized. DCFA has elements of both a commons and a market approach and is made possible by CR technology. The relative openness of the new PMC spectrum block has elements of a commons situation. There are still restrictions on becoming a MNO, but they have less control and ownership over the spectrum now. Limiting PMC transmission will remain a necessity. If everyone can start
long-range transmissions, an eventual (and preventable) tragedy of the commons will occur again, even with CR-based technologies. This is because PMC spectrum is still a locally limited resource. If technology allows it, people can make use of much more spectrum for all sorts of short-range applications. The limitations of transmitters deal with the local scarcity of spectrum the same as before.

Payments for infrastructure usage take a more market approach by using real-time bidding. Again, this is made possible by the self-governing nature and learning capabilities of CR technologies, and the speed at which real-time bidding can take place. Even if radio spectrum itself has become less scarce as a result of technology, there is still a need for infrastructure and its maintenance. This will result into a situation where, over time, users pay the lowest possible price for using PMC infrastructure and aren’t locked into contracts anymore. The lowered barriers of entry to becoming a (more local) MNO are also in the spirit of the market approach. In the end, it’ll lead to more competition and less geographical areas that aren’t serviced properly by the current system.

There is still some top-down regulation left: Spectrum allocation is still a task of a national governments and the global community via the ITU. The monitoring of the MNOs and the real-time bidding process is also done by a national government. The real-time bidding can essentially be done automatically via software. The Intermediate facilitates the auctions and is vital in DCFA and may prove to be the weakest link: if it is tampered with, it can result in unfair auction results. Careful monitoring by a national regulatory authority will be necessary, but this is also the case with MNOs today. Since this can be a software layer that exists on phones and base stations, having it be open source would be a great start in keeping the process transparent. If could also be managed and checked by an NRA or another consumer organization if this is deemed desirable. When moving to a single European market, all parties involved must have a dialog about subjects like privacy.

Spectrum assignment and the parameters of spectrum access are now controlled by the base stations and user devices themselves. This is done fully automatically and will be done in a way the delivers the best possible QoS. Table 6 provides an overview of some major changes between the current command and control paradigm and DCFA.

<table>
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<tr>
<th>Decisions</th>
<th>Command and control</th>
<th>DCFA</th>
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<td>Spectrum allocation</td>
<td>Governments and standard bodies</td>
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<td>Spectrum assignment</td>
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<td>MNO choice</td>
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<td>QoS</td>
<td>Governments (emergency services) and MNO (normal service)</td>
<td>Governments (emergency services) and Intermediate (normal service)</td>
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Table 5: Changes between the command and control and DCFA.

6.1.3: Why this new paradigm?

Any changes that are made to the current spectrum management paradigm will have major consequences throughout the world. PMC services cover the world and many people and companies rely on its functioning. There has been a huge buildup of regulations and routines that surround the current paradigm. But this isn’t the first time the spectrum management
paradigm has changed: Chapter 3 talked about the switch from government control to command and control. Chapter 1 discussed the growing shortages of spectrum: DCFA is an opportunity to utilize radio spectrum better and solve these problems. The time to transition is now, since there will be a steep increase in wireless applications in the near future.

The new technology is another reason to implement DCFA. Cognitive radio has many advantages and Chapter 2 argued for why cognitive radio should be implemented in the area of PMC. A CR-based system within the confines of a command and control paradigm could still alter its parameters, and still learn over time what the optimal configurations are in certain situations. Base stations even have some self-adjusting capabilities today. If someone calls an emergency service, they are automatically given priority access to the infrastructure. But, there won’t be as many configurations of transmission parameters to choose from. The more spectrum a CR system can use, the better it can optimize itself over time. The sustainable consumption of spectrum as a whole will rise if it is pooled together to be used for DCFA.

Perhaps the biggest reason to implement DCFA in the long term is innovation. As discussed in Chapter 3, DCFA eliminates the PMC spectrum bands and exclusive spectrum licenses. This essentially gives people a bigger say over the useful portions of the radio spectrum. Radio spectrum is the owned by the people (through the government) after all. All current short-range devices are tied to a few open bands like the saturated ISM band. They will now be permitted in the entirety of the new PMC pool. This provides society with huge opportunities to innovate and develop new applications leading to an increase in the social value of radio spectrum. It essentially allows people to utilize a resource that otherwise would go to waste. People also get a bigger say over a natural resource that belongs to all of us.

DCFA also has many monetary benefits for different actors. Users aren’t tied to one MNO via a multi-year contract or a carriers specific pre-paid SIM anymore. Because of the reduced scarcity of spectrum, overall access prices can be expected to drop over time. MNOs will not have the upfront costs of spectrum auctions any longer. One could argue that this is only a small portion of the current price that users pay for access. This is because even though the price that is set by an auction is high, the spectrum is licensed for a long time and the amount of users that can be served with it is also very high. The biggest savings will be made on the operational side of things (Opex). The resulting lower prices that users will have to pay to transmit data will make it more feasible for new applications that rely on long distant PMC networks to be developed and implemented. Users can make use of more of these new services thanks to the much lower costs of infrastructure access.

DCFA can offer a road towards a single European market. This has been a part of the European Commission’s agenda for quite some time now, as discussed in Chapter 3. There have been steps towards this, but the issue of roaming costs has been a pain point in the negotiations between the different member states. DCFA allows for MNOs to get paid based on the percentage of data traffic they’ve facilitated. The Intermediate system can be expanded over time to become a European system instead of a national one. During or after this transition, MNOs can simply choose to offer slightly higher prices for roaming customers if they find that necessary. Real-time bidding forces a form of “instant democracy”: market forces can quickly bring roaming access to acceptable prices.
6.2: DCFA and common-pool resource management

6.2.1: Property rights and DCFA
Radio spectrum has always been difficult to discuss in the areas of property rights and CPR management because of its unique nature. It is susceptible to the tragedy of the commons but it can never run out. Its property rights have always been split up into different levels of ownership ever since the first legislation surrounding radio transmissions in the 1920s. All radio spectrum starts out as an open access CPR: all radio spectrum is owned by mankind as a whole. DCFA does not fall on open access even though technology may allow it. The tragedy of the commons still applies, and every party transmitting without consequences leads to unnecessary interference. Supercommons is also not chosen as a starting point: it lacks property rights and has too little safeguards against over-usage and unnecessary use. Liability may be a proper tool against this, but DCFA handles these problems more effectively by preventing them instead of solving them. Supercommons also ignores the CPR nature of radio spectrum.

Radio spectrum, as a subset of the electromagnetic spectrum, has been treated as a government property for most of its history (starting with the first radio transmissions by Marconi). Governments have been the owners and proprietors of the resource. The PMC sections of the radio spectrum added MNOs as claimants and users as authorized users. The open sections of the spectrum simply have everyone as an authorized user.

DCFA keeps the government as the owner and proprietor of PMC spectrum. The restrictions that a government as the owner and proprietor of radio spectrum puts on the resource itself, are to the benefit of everybody. MNOs are demoted in DCFA from proprietors to claimants: they can no longer decide who to offer service to or set service restrictions. They simply build and maintain the infrastructure necessary to use radio spectrum. Users remain authorized users in the area of long range PMC. They become claimants in the case of short range applications: they can set up their own applications in the PMC pool. In the end, PMC radio spectrum is still owned by a form of government and is therefore a government property. When looking only at short range applications, the PMC pool acts more like a group property.

6.2.2: DCFA and CPR management: payment
The method of payment in DCFA fits with the nature of radio spectrum as a special kind of CPR: globally infinite, but locally constrained. Its supply and demand are constantly slightly different: the degree of base station density can widely vary per area, the number of users varies per area and per time of day, and the amount of data that is transferred varies per time of day as well. DCFA with real-time bidding will manage spectrum better both technologically and economically, and the burdens and benefits will be balanced more equally. It can be considered fairer to pay for the data you actually use instead of buying a set amount of data each month. One of the reasons the users are charged a fixed amount of money per a fixed amount of data is to make it easier for them to choose an MNO. Users can compare which of them has the best price for the next two years. This decision making on the user’s part will no longer be necessary with real-time bidding in DCFA.

6.2.3: DCFA and CPR management: Ostrom’s design principles
The guidelines set by Ostrom to manage a CPR can be used as a check for DCFA. After all, radio spectrum is a CPR that is beneficial to all people and must be managed properly. There are eight design principles that Ostrom defined for long and sustainable CPR management paradigm. These were discussed in more detail in Chapter 4 and will be used to provide a test
for DCFA. The discussion of these rules also looks at differences between the current system and the new system.

1. **Cleary defined boundaries of the resource and their property rights.**

   DCFA has clear property rights: the big pool of PMC spectrum is clearly defined as well as who can offer PMC services using that spectrum. As shown in the previous section, each party has a level of property rights attached to them. All of the different actors will know what their specific role is.

2. **Proportional equivalence between benefits and costs.**

   The benefits and costs are redistributed to some extent when compared to the old situation. Most importantly, CR technologies allow for spectrum to become less scarce and reduce the actual costs to infrastructure access. This reduces the costs of the actual resource thus improves the overall situation for all actors. MNOs will still be compensated for their services, and don’t have the big upfront costs of spectrum auctions anymore. So they’ll have lower costs, but they’ll also have lower benefits as a result of the lower access prices that will be paid. These are expected to balance out over time because of market forces. Users see more benefits in terms of cheaper spectrum access and more freedoms for low range applications. They will see higher upfront costs because of the device they’ll have to buy, but they pay for that today one way or another. Government’s costs will include the monitoring but they have these costs today. They do miss out on big sums of money from time to time that came in as a result of spectrum auctions. This will most likely be compensated over time thanks to increase of innovation and economic activity because of better spectrum use.

3. **Collective choice arrangements.**

   The choice arrangements surrounding the rules of spectrum access can’t be fully collective unfortunately. This principle is more applicable to smaller scale and local CPR usage. If rules and regulations surrounding spectrum management need to be changed, they must come from the top: the government, the EU, and standards bodies. Radio spectrum doesn’t stop at any border, and using it causes great network effects making it hard to manage with many different parties. Because of this unique nature of radio spectrum and the infrastructure that is needed to use it, rules and regulations will still have to be set at the top. MNOs aren’t incentivized to break them however, because they’ve invested a lot into building an infrastructure. In a worst case scenario, they could be forced to give up their MNO status by a government. There is incentive to keep infrastructure access pricing high, something which real-time bidding and careful monitoring has to prevent. Users aren’t incentivized to break these rules them either due to the cost and expertise need to build their own custom transmission equipment. All of these incentives are no different than the incentives in the current situation.

4. **Clear monitoring.**

   Most of the monitoring today is done by a NRA, which will not change with DCFA. It also needs monitoring in software: the Intermediate that handles the auctions must remain transparent to all parties involved. Devices will have to be monitored as well, which can be done with the same approval process today’s devices undergo. All of this can be considered feasible, as it will not be much different from the old situation. The actual interference temperature is constantly being monitored by the MNO’s base stations. If any user starts breaking transmission limitations those base station will be able to detect that.

5. **Clear sanctions.**

   Again, this will not be much different than the old situation. MNOs that break the rules by colluding price wise or by obstructing the bidding process can financially be punished. Any users that break transmitter limits in the PMC spectrum, can be financially punished as well.

6. **Conflict-resolution mechanisms**
To avoid conflict, it’s vital that the rules of DCFA are defined properly and unambiguously. This chapter provided a basic outline, but further research is needed to make DCFA more concrete. The main conflicts that can still occur can be related to interference and access pricing. DCFA can resolve conflicts automatically: transmission parameters are changed automatically by CR technologies, and real-time bidding resolves pricing issues in favor of the user.

7. *The right to organize*

Every actor in the current system has some right to organize, and they will have the same rights in DCFA. Governments are per definition organized, and work together in unions like the EU. Proponents of technical standards are organized under the standard bodies like ITU and ETSI. MNOs are organized in the GSMA and can continue to do so. Device manufactures mainly compete and have no big reason to organize. Users can organize in different consumer organizations and will also continue to do so. But now they have the option to set up a local PMC network themselves and collectively become an MNO if they want to.

8. *Nested enterprises.*

PMC management is nested to a certain extend. Global standards bodies set standards for different levels of government (EU and national). In turn they set rules for MNOs and device manufactures. This remains unchanged, with the addition of the Intermediate that handles the real-time bidding.

6.2.4: *DCFA and CPR management: Ostrom’s adaptive governance.*

Since technologies and requirements that surround PMC and other radio transmission applications change constantly, DCFA also needs to be adaptive to handle inevitable changes that occur in the landscape. Ostrom defined adaptive governance, which was discussed in Chapter 4 as well.

1. *Achieving accurate and relevant information.*

Due to the cognitive nature of CR, there is a constant supply of data about the interference temperature etc. that surround the everyday functioning of DCFA. There is also a lot of information about prices paid for infrastructure access, number of devices sold, industry profits and so on. All of this makes it so necessary changes to DCFA can be spotted far in advance.

2. *Dealing with conflict, and 3. Enhancing rule compliance*

These are similar to no. 4, 5 and 6 of the general CPR design principles.

4. Providing infrastructure.

The technological infrastructure is provided by the MNOs and device manufacturers. Since these are CR based they are inherently flexible and with a proper forward looking and new air interface, this infrastructure can be expected to suffice for the foreseeable future.

5. Encourage adaptation and change.

DCFA has been globally defined in this paper in terms of set up and the roles of different actors. There is still a need for technological advancements, debate about regulations, and testing in the real world before anything can be implemented. The current definition of DCFA can change and because of the cognitive nature of the technology, small and short-term changes can easily be made. However, it’s hard to predict what long term changes will need to happen, especially in a global CPR paradigm with many network effects. As shown by looking at the last 25 years of PMC management, once transition is made to a PMC paradigm it’s hard to move away from it again. It’s simply not feasible to set up a PMC management paradigm in any flexible manner.
In conclusion, DCFA fits with Ostrom’s design principles for the most part. There just isn’t room for parties like the MNOs and users to have much of a say in the changing of rules and regulations, because of the global nature of radio spectrum. Those rules and regulations are hard to change in general because of their global reach and the network effects of PMC. But given the clearly defined property rights, benefits and costs distribution, and automated conflict resolution DCFA can be considered to be a suitable paradigm to manage a CPR. It being a better paradigm will be made possible by CR-based technologies.

6.2.5: DCFA and social value
As discussed in Chapter 4, the current command and control paradigm does not sufficiently meet the societal demands of spectrum and spectrum infrastructure. DCFA improves the situation in this regard mainly thanks to CR technologies. The infrastructure remains in hands of market parties (the MNOs) and long range access remains restricted. The infrastructure still has a price, but the positive spillovers of DCFA are available to all of society. The PMC spectrum pool can now be used for all sorts of new activities resulting in innovation and novel applications. This increases the social value of spectrum thanks to the new spectrum infrastructure: the new CR technologies built into the base stations partly allow for this to happen. The monetary investment that needs to be made to increase this social value is needed anyway to implement the new paradigm.

6.2.6: Future steps, and recommendations for all parties
There are many steps to take in order to arrive at this new paradigm. The general timing seems relatively favorable at first glance: the 4G LTE rollout is complete in most of the world including Europe, and discussions about its successor are ongoing. There is also pressure from the overall landscape surrounding all wireless transmissions. Open bands like Wi-Fi in the 2.4 GHz band are locally saturated, and the number of PMC users is still growing. Users can experience slowdowns or a lack of service in busy geographical areas today.

There is much research ongoing and much more research to be done in the field of CR technologies and air interfaces. This new paradigm rests on the notion that the technology will be ready and suitable for long distance transmissions in the field of PMC. The current interest and research in the field of CR technology is substantial and there is an ever growing interest for the successor to 4G-based technologies from both governments and private parties. LTE was developed by a huge number of parties from all over the world, over a long period of time. Parties like the EU would do well to invest money and other resources into research about the next generation of wireless interfaces for PMC and viability of DCFA. The EU’s Europe 2020 and Horizon 2020 program are already in place luckily. Governments will have to work together strongly for DCFA to become a success, and they must all agree on what the PMC spectrum pool should be and how the internal market will work. There will also be a need for cooperation with private parties: the MNOs, standard bodies, researchers and various other IT companies. This was also done with previous generations of PMC. Luckily there is already a public-private partnership in place called the 5G-PPP. This is spearheaded by the EU as part of their Europe 2020 program. They are current developing proposals for new standards and have included cognitive radio in their research (Networks, 2011).

The standardization of 5G may be in a too far advance stage to introduce a paradigm shift. As discussed, a big part of the 5G is the air interface. These leaves the possibility of missing the “5G deadline” and adding DCFA and changing the spectrum management paradigm later. There may also be a period were different possible DCFA standards compete. Think again of difference in the air interface, but also the bidding process etc. It is vital for policy makers of national governments and the EU, researchers, private companies and standards bodies to
come together quickly and discuss the implementation of CR technologies into the next PMC standard. The clock is ticking and many parties have 2020 as the year they want first drafts of a new standard to be ready.

Policy wise, DCFA changes the way spectrum allocation and assignment is done. The spectrum auction system will make way for the big PMC spectrum pool. Governments will have to set up new policies for becoming an MNO, and the demands that are placed on them. Governments will have to set up new policies for short range applications in the PMC pool as well. They can be based on current recommendations from standards bodies and the existing CUS framework. These restrictions should be a technology agnostic as possible, to stimulate innovation in this field. Governments and the EU will have to check what legislation needs to change to implement DCFA and the real time bidding market, and how realistic it is to do so. As discussed in Chapter 3, spectrum harmonization among member states is important. Different governments and the EU will have to work together closely to produce the optimal result, and arrive at one common spectrum pool.

MNOs will need convincing because they will lose some of the control they currently have. They are organized under the GSMA and they will lobby to not lose that control. In the end, communications and the optimal use of radio spectrum is in the interest of all of mankind. Government is supposed to propagate these interest and must therefore set course to implement DCFA. One advantage is that there is already a huge infrastructure of base stations operational today. There will not be a need for big investments from the MNOs like in the early days of PMC. MNOs will still be properly compensated based on the outcomes of real-time biddings. Devices that are sold will still have to be certified, which will be similar to the current situation. The real-time bidding and billing will require a whole new set of policies. These need to be carefully crafted in order to satisfy all parties, and discourage/prevent misuse. Once DCFA is set to be implemented, MNOs should examine the steps that are necessary to move over to the new paradigm as quickly as possible.

Other big step towards the implementation of DCFA is testing, both of the technical implementation as well as the payment side. As previously said, spectrum that is planned for future PMC use (700 MHz and 1700 MHz) is very suitable to test the technical implementation. Governments should facilitate this testing by opening up this spectrum for it. Testing will include things like regular transmissions, emergency transmissions, switching MNO, adapting to new RF environments, and the uses of short-range equipment and military applications in the PMC pool. There have to be proof of concepts that a long range PMC system can function properly based on cognitive radio technologies. Many papers speak of the promises of the technology, but actual real world testing will ultimately provide the answer. Testing can happen more locally at first, requiring less parties to cooperate. If they are successful, more companies and governments will want to get on board. Testing offers invaluable lessons about the technology, practical implications and limitations, and the needs and motivations of different actors. Not everything can be planned and predicted beforehand.

The real-time bidding system and new billing system are new to PMC: these need to be tested as well. One way to conduct this testing is by using a VNMO. They currently operate on the physical network of one MNO. You could set up a VNMO to operate on all of the major networks, and set up the real-time bidding system and the Intermediary on a testing subset of all major MNOs. Test users can be given a DCFA enabled phone and test out the new payment system in that test area.
To summarize:

- Governments and the European commission must discuss the implementation of DCFA and move to put legislation in place to make this possible. They should investigate the legal implications of DCFA. There is a lot of legislation surrounding PMC and MNOs, which will have to change in order for DCFA to be implemented.

- Governments must also work together closely with private parties like MNOs, infrastructure manufactures and mobile equipment manufactures and direct them to producing CR based equipment. There should be testing as soon as possible to validate the possibility of a CR based PMC network. This must include both the technical side and the payment side of DCFA.

- Governments and the EU must push CR technologies along with the new DCFA framework with the standards bodies like ITU and ETSI.

- MNOs should investigate what steps are necessary to transfer their infrastructure over to DCFA.

- MNOs and governments should also test and investigate the implementation details of the real-time biddings.
7: Conclusions and Discussion

7.1: Conclusions
At the beginning of this paper the main research question was stated as:

Can cognitive radio technologies enable a new paradigm of spectrum management in the field of personal mobile communication?

The short answer is yes: cognitive radio technologies can enable a new paradigm of spectrum management. It can change the PMC space to be more efficient and it can enable a better management of radio spectrum as a natural and common-pool resource. It can replace the inefficient command and control system, help to solve the growing spectrum shortages, and allow for more applications in the PMC space. There are some limitations and assumptions in this paper, which will be discussed. First, the sub-questions will be examined.

1) How can cognitive radio contribute to meeting future requirements in mobile communications?
As shown in the introduction, the main requirement of the next generation of PMC and other mobile communications is more capacity. The number of users in the PMC space keeps growing, as does the number of new applications that use radio transmissions. Because long range PMC transmissions use a static combination of frequency, bandwidth and transmission power, the radio spectrum has been divided up into bands. These bands contain whitespaces and spectrum holes and are an inefficient way to manage spectrum: they contribute to the problem. CR can automatically configure itself change transmission parameters whenever this is necessary. It can also learn over time and improve its performance over time. This will lead to a much more efficient use of the available spectrum, and it will result in a decrease of operating costs. If nothing else changes, there will only be a marginal improvement. But if spectrum gets pooled together into a big spectrum pool which a CR based system can manage automatically, there can be major improvements to efficiency. Given that there will always a limited part of the spectrum suitable for long range PMC transmissions, using that spectrum more efficiently is the best approach to keep up with growth. CR-technologies can also enable more short range applications to operate in the PMC spectrum, since the longer range transmissions can be reconfigured if necessary.

2) What does a new framework for implementing cognitive radio look like? (i.e. what needs to change in the current paradigm of mobile communications?)
This question has been answered all throughout Chapters 5 and 6. The new framework is called Device Controlled Frequency Access, and it fundamentally changes PMC spectrum management. It pools as much spectrum together as possible and opens it up to all MNOs, which will provide PMC services. Again, this is all made possible by CR technologies. Now that all PMC spectrum is accessible to all MNOs, more local MNOs can easily be set up. They can service extreme situations like extremely sparse or extremely dense populations. This is partially made possible because of the absence of licensing costs, which would otherwise make smaller MNOs and network impossible. Users will no longer sign a contract with an MNO, but change between them based on a MNO’s offerings in terms of QoS and price per data unit. These can be reoffered to the user via a real-time bidding whenever necessary. The Intermediate facilitates these biddings and keeps track of data usage among
the various networks. It also bills the user at the end of the month and distributes this money to the different MNOs based on the amount of data transmissions they have facilitated.

All the major differences between DCFA and the current situation have been discussed in the previous two chapters. It is safe to say that it is radically different than anything we’ve seen since the introduction of the current command and control paradigm. It will be a relatively big change, but the current system is based on old technologies and it has hindered more efficient spectrum use.

3) Will radio spectrum be properly managed by this new paradigm?
Because radio spectrum is a unique natural and common-pool resource, it is hard to find a standard solution that tells you how to manage it. DCFA does deal with this unique nature better than the current paradigm of command and control. Spectrum is infinitely reusable and renewable, but it’s scarce locally and temporally. Real-time biddings and CR-technologies deal with this issue automatically. It remains difficult to answer this question definitively. The theories of Ostrom were used as a testing framework and DCFA fits with the rules that are set by those theories. It is a unique combination of a commons approach and a market approach. PMC spectrum is a government controlled CPR, the short-range application of the spectrum belongs to the commons, and access to PMC spectrum is regulated by a real-time market. In the end, DCFA will allow for a more efficient use of the available radio spectrum and will allow for more and new applications to use this spectrum. It is more beneficial to us all, as it should be because the radio spectrum belongs to all of us.

7.2: Discussion points
This section will discuss some aspects and conclusions of this paper that remain open for discussion.

7.2.1: Technology
The first major point of discussion surrounding this topic is the underlying technology. As of the writing of this paper, CR technology is still being developed. Many aspects surrounding CR like spectrum sensing, machine learning, and the analysis of RF stimuli are currently being researched and debated (often by members of the IEEE). Looking at papers from the last 10 to 15 years, the technology is becoming more capable and better understood at a high pace. This paper’s conclusion does rest on the notion that CR based technologies will be (a) suitable for PMC and (b) ready in time for the specification of the next standard. This can be considered the biggest discussion point of this research: the technology looks promising but there is still an uncertainty of the viability for long range PMC applications. The other half of the technology side are the mobile phones that people will use. These will have to have some spectrum sensing capabilities to update the base station’s information. As discussed in Chapter 2, there are proof of concepts today, but these will require further testing.

7.2.2: DCFA as part of a 5G standard
This paper has referred to CR the new technology for PMC, but CR technologies can be used in conjunction with many different other technologies. There is an opportunity to incorporate CR technologies into the next generation of PMC (5G). Luckily, the specifications for this next generation are still in the stages of development and standardization. Many different parties are contributing to this discussion, and the EU has taken a leading role into developing a new 5G standard. This provides an opportunity for the EU and its member states to set stage for a new and more efficient paradigm in PMC. However, DCFA is more than a new standard. It’s an entire overall of the PMC paradigm, making it very difficult to implement. One could argue that because of the big changes to the whole spectrum paradigm, DCFA is
actually too late for the 5G standard. Many policy documents and company papers talk about 2020 as the target date for the first 5G specifications.

7.2.3: MNOs in DCFA
The real-time bidding between different MNOs with an intermediate party can be considered somewhat convoluted and complicated. It will also be criticized because it’s such a big departure from the current situation. Especially the MNOs themselves will heavily protest this new system because they will lose a big part of the control they currently have, even though they’ll no longer have huge upfront costs due to spectrum auctions. This new system is made possible because of relatively cheap amounts of computing power that is available today in conjunction with CR capabilities. It simply wasn’t possible when the current command and control paradigm was being built, but that is no reason to stick with that paradigm. In the end, testing and a large scale cost-benefit analysis will have to provide an answer to the desirability questions surrounding real-time bidding.

7.2.4: Common-pool resource theories
This paper referred to spectrum as a unique common-pool resource. It therefore used theories related to CPRs to analyze spectrum in the current situation and in DCFA. One point of discussion is that because of the unique nature of radio spectrum, current CPR theories aren’t fully applicable. There simply aren’t many papers that focus on spectrum specifically when discussing CPRs. There is plenty of research that talks about adding spectrum to the commons, but these are still rooted in current technologies and deem it not viable for the most part. Having spectrum added to the commons also implies little or no restrictions to access like for instance Supercommons, which is at odds with CPR management theories.

7.3: Viability, limitations, and future research

7.3.1: Viability
In the end, DCFA can be considered viable to implement. It has some big hurdles to overcome and some switching costs attached to it. The first of these is the standardization of a new PMC standard, which is a length process and can be influenced by many different parties. CR systems are being considered as a possible addition to a next generation standard, but it’ll be developed based on the current command and control paradigm. Once national governments and the EU see the benefits of a new paradigm like DCFA, one can expect policy changes to be implemented. It’s just a matter of timing and cooperation: policy maker must decide on DCFA and must then guide companies and standards bodies to implement CR technologies into the standard.

The actual practical implementation of CR technologies will be relatively easy: if a new technical standard based on CR-technologies is developed, all of the spectrum and base stations can slowly be transitioned over to DCFA. The big spectrum pool is heavily depended on the capabilities of CR to not interfere with short range applications in the open spectrum and military applications. The biggest switching cost is the new access payment system that makes DCFA such a different paradigm. This aspect makes the whole implementation seem difficult at best, and unfeasible at worst. The quicker this system is developed, debated, and tested, the more information will be available to all the relevant actors. This is the way to make the implementation of DCFA viable.

7.3.2: Limitations
One of the biggest limitations of this paper is the lack of quantitative data about the data throughput improvements of CR-based systems. More data on this would provide better insight into the possibilities of DCFA. Data about the increase in data throughput,
combinations with different air interfaces, the ability change frequency and bandwidth etc. would all provide better insight into the viability of DCFA. The lack of tests with long-range CR systems are also a limiting factor.

Another related limitation has to do with CR technology as well. Since the technology is being developed at a high pace, there could be new information relevant to this paper that hasn’t been included. This is an issue that plagues every scientific paper. The same goes for regulations and policies set by the EU. The legislative field surrounding telecommunications is very large. There are also new press releases and policy updates regarding radio spectrum on an almost monthly basis.

DCFA was checked by using the theories on CPR by Ostrom (1990/2008). The biggest weakness of DCFA is that it still requires regulation from the top-down, where her theories also pushed for as much local management as possible. This is achieved to some extend with short-range application, local MNOs, and real-time biddings but there will always be a need for top-down regulations in the PMC field.

7.3.3: Future scientific research
The most immediate step for future scientific research will be the implementation of CR technologies for PMC applications. There is sufficient research on CR in general, including research on spectrum sensing, game theory etc. New research should focus on long range transmission, based on a CR system and with many different users in one area. It should also look at its ability to not interfere with short range technologies (including Wi-Fi) operating in the same bands. There also needs to be more research into the best way to manage spectrum as a CPR and natural resource in general. Just opening it all up and adding it to the commons is not a good solution, but current CPR theories do not fit very well with radio spectrum.

There are other topics surrounding PMC that would benefit from further research. One of them is privacy. MNOs can gather a huge amount of data about someone based on the data they transmit/receive and the location that they do this from. DCFA separates the consumer from the MNO in the sense that they no longer sign a contract with one of them. They hop between them based on the result of the real time bidding. The Intermediate is now the one that keeps track of the user. It would be worthwhile to research if the user could completely be anonymized. If a user pre-pays anonymously to the Intermediate, there is no reason for any MNO to have their personal data.

Another topic of future research could be the existence of the MNOs themselves. Are they still necessary in the DCFA paradigm? A government could technically provide the infrastructure and guarantee a certain QoS or guarantee certain services like they do today with emergency services. This is also in line with something that Frischmann (2012) proposed: all infrastructure should be managed as a commons whenever possible. Current legislation is setup to foster competition between MNOs, but with DCFA this may no longer be necessary. A government as MNO may eliminate the need for real-time biddings. Users could simply pay using a tax, or in the case of a European wide network, pay via an added cost to the device.
References


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