Stratix

Dynamic Spectrum Management & Sharing

REPORT

Study assigned by
Radiocommunications Agency Netherlands
Ministry of Economic Affairs and Climate

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Management Summary

More and more information is being transported using wireless technologies. In some places and at certain times, parts of the radio spectrum are overused or in danger of being overused. But on the other hand a large part of the assigned radio spectrum is hardly used, or only used locally or at particular moments. More dynamic sharing of spectrum could be a solution to ensure sufficient availability of spectrum in the future.

This report provides the result of a study requested by the Radiocommunication Agency Netherlands with the aim to identify feasible concept(s) and technologies that can be the starting point for more advanced, more dynamic and smarter approaches to spectrum sharing and related spectrum management, which could be considered to be piloted in the Netherlands. The study provides an overview of spectrum sharing methods, technologies and (potentially) usable frequency bands, an assessment of aspects relevant for potential pilots, and recommendations on feasible pilots and proof-of-concepts.

Ideally, pilots and proof of concepts should provide a test case for innovative solution approaches that can potentially solve spectrum scarcity for certain users or user types, or in certain locations in the Netherlands. We conclude that a pilot or proof-of-concept that is interesting for stakeholders and user groups in the Netherlands, and is also internationally technologically relevant, is feasible in the Netherlands, and can be based on existing technology and existing protocols with some specific innovative enhancements. It should preferably use some form of sensing (beyond simple "listen before talk"), in combination with a dynamic reservation mechanism such as a central database. Such an approach would require some software development, using existing hardware.

It is also possible to base a pilot entirely on mature technology. While not technically innovative, such a pilot could still explore the legal, organisational and commercial aspects of sharing. For such a pilot, a central database mechanism would be sufficient, combined with a set of rules for the use of spectrum inspired by the US Citizen Broadband Radio Service (CBRS) system.

The most relevant of the bands to test the identified concepts in the Netherlands are the DVB-T2 band, the 3.8-4.2 GHz band, the 6 GHz band, but also some existing radar bands (in particular the X-band) and the 26 GHz future 5G band.

Necessary arrangements, rules or standards differ per solution area with regard to spectrum sharing. While workable examples exist for these arrangements, extensive collaborative effort and guided discussion will be needed to establish communication and trust between (primary and secondary) users in order to successfully implement them in the Netherlands. In order to get the cooperation of primary users, it may be necessary to add conditions to future spectrum licenses.

For potential pilots, trials and/or proof-of-concepts in the Netherlands of dynamic spectrum sharing applications the study recommends to focus on "spectrum hot spot" areas where many different organisations or users use radio spectrum extensively and where a local solution can provide advantages for multiple parties.

In the Netherlands, permanent spectrum hot spot areas are Schiphol Airport and the Rotterdam seaport. There are also temporary hot spots surrounding large events (Sail Amsterdam, music festivals, etc) as well as in the case of the emergency services and disaster situations. Although disaster situations themselves are not likely to be suitable pilot candidates, controlled practice situations may very well be.

A general observation from both the research and the interviews is that to achieve proportional and lasting efficiency improvements using dynamic spectrum sharing, finding the right combination of stakeholders, and organisational and regulatory aspects are more important than technology. It is rather challenging to find a use case that effectively shows the benefits of spectrum sharing in a pilot situation of some scale: in situations where spectrum is scarce, primary users don't like to experiment, and in

situations where spectrum is not scarce the pilot does not really demonstrate the advantages of dynamic spectrum sharing.

On the other hand, primary users may be willing to cooperate if the concept not only allows for sharing of relatively unused spectrum with other users, but also provides them with benefits, for instance by allowing them to use more spectrum during emergency situations.

Managementsamenvatting

Steeds meer informatie wordt door de lucht getransporteerd, gebruik makend van draadloze communicatietechnieken. Op sommige plaatsen, en op sommige momenten, zijn daardoor grote delen van het radiospectrum volledig in gebruik, of dreigen ontoereikend te zijn voor de vraag naar capaciteit. Anderzijds is is ook een flink deel van het aan verschillende partijen toegewezen radiospectrum juist vrijwel ongebruikt, of wordt het alleen gebruikt op een bepaalde plaats, of alleen op bepaalde momenten. Het delen van radiospectrum op een meer dynamische en slimme manier dan tot nu toe gebruikelijk is kan een oplossing zijn om voldoende beschikbaarheid van radiospectrum te kunnen garanderen, en efficienter gebruik van radiospectrum mogelijk te maken.

Dit rapport bevat het resultaat van een studie die is uitgevoerd in opdracht van Agentschap Telecom. Het doel van de studie is om bruikbare en haalbare concepten en technologieën te identificeren die gebruikt kunnen worden als basis voor geavanceerde, meer dynamische en slimmere benaderingen om radiospectrum te delen en het beheer daarvan te regelen, en die wellicht ingezet kunnen worden in een pilot project in Nederland. Dit rapport biedt een overzicht van verschillende methoden en technologieën om radio spectrum te delen, welke frequentiebanden daar (potentieel) bruikbaar voor zijn, welke aspecten relevant zijn voor eventuele pilots, en aanbevelingen over welke pilots en proof-of-concepts het meest haalbaar zijn.

In het ideale geval vormen pilots of proof-of-concepts een test case voor innovatieve oplossingsstrategieën die een bijdrage kunnen leveren aan het verkleinen van spectrumschaarste van bepaalde gebruikersgroepen of in bepaalde plaatsen in Nederland, en die nog niet elders in de wereld getest zijn. We concluderen dat een pilot of proof-of-concept dat interessant is voor stakeholders en gebruikersgroepen in Nederland, en dat ook internationaal technologisch relevant is, in Nederland mogelijk is, op basis van bestaande technologie, met enkele pilot specifieke innovatieve aanpassingen. In een dergelijke pilot zou bij voorkeur gebruik gemaakt worden van een complexe vorm van 'spectrum sensing' in combinatie met een reserveringsmechanisme zoals een centrale database. Een dergelijke aanpak vereist enige software development, maar er kan bestaande hardware gebruikt worden.

Het is ook mogelijk om een pilot volledig te baseren op volwassen technologie. Ondanks het feit dat dit niet technologisch innovatief is zouden in een dergelijke pilot wel de juridische, organisatorische en commerciële aspecten van het dynamisch delen van spectrum verkend kunnen worden. Voor dergelijke pilots is het opzetten en beheren van een centrale database voldoende, gecombineerd met een set van regels voor het gebruik van radiospectrum, geïnspireerd op het Citizen Broadband Radio Service (CBRS) systeem dat in de Verenigde Staten is ontwikkeld.

De meest relevante van de mogelijke spectrum banden waarin de geïdentificeerde concepten in Nederland zouden kunnen worden getest zijn de DVB-T2 band, de 3.8-4.2 GHz band, en de 6 GHz band, maar mogelijkerwijs ook enkele bestaande radar banden en de toekomstige 26 GHz mobiele band.

De daarbij noodzakelijke afspraken, regels of standaarden verschillen per oplossingsrichting die gebruikt wordt om spectrum dynamisch te delen. Hoewel er werkbare voorbeelden bestaan voor dergelijke afspraken is het voor het opbouwen van een goede communicatie en vooral vertrouwen tussen de (primaire en secundaire) gebruikers nodig om veel energie te steken in intensieve samenwerking tussen de relevante stakeholders en de discussies daartussen goed te begeleiden zodat deze voorbeelden in Nederland succesvol kunnen worden geïmplementeerd.

Voor potentiële pilots, trials of proof-of-concepts in Nederland van toepassingen op het gebied van het dynamisch delen van spectrum beveelt de studie aan om te focussen op 'spectrum hot spot' gebieden, waar veel verschillende organisaties of gebruikers het radiospectrum intensief gebruiken en waar een lokale oplossing voordelen kan bieden voor meerdere partijen.

In Nederland zijn Schiphol en de Rotterdamse haven voorbeelden van permanente spectrum hot spot gebieden. Maar er zijn ook tijdelijke hot spots zoals rond grote evenementen (Sail Amsterdam, muziekfestivals, etc), of in het geval van hulpdiensten en calamiteitensituaties. Hoewel die laatstgenoemde situaties op zichzelf geen geschikte pilot kandidaten zijn, een gecontroleerde oefensituatie is dat mogelijk wel.

Een algemene observatie op basis van zowel het literatuur onderzoek als de interviews is dat het vinden van de goede combinatie van betrokken relevante organisaties (‘stakeholders’) en de organisatorische en regelgevingsaspecten belangrijker zijn dan de technologie. Het is behoorlijk uitdagend om een niet missiekritische of bedrijfskritische use case te vinden die gebruikt kan worden in een pilot van enige schaal om de voordelen van het delen van radiospectrum te demonstreren: in situaties waar spectrum schaars is willen primaire gebruikers niet graag experimenteren met het delen van hun schaarse spectrum, terwijl in situaties waar spectrum niet schaars is een pilot potentieel niet of nauwelijks de voordelen van dynamisch delen van spectrum aantoont.

Aan de andere kant kunnen primaire gebruikers mogelijk geïnteresseerd zijn om mee te werken aan een pilot als het concept dat wordt getest er niet alleen voor zorgt dat het spectrum van deze organisaties kan worden gedeeld met andere gebruikers, maar ook voordelen biedt voor deze organisaties zelf, bijvoorbeeld omdat ze daardoor gedurende noodsituaties juist meer spectrum kunnen gebruiken.

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1 Introduction

1.1 Background

Electronic communication services are growing in importance in today's society. Sufficient radio spectrum for (mobile) services is an important precondition. However a large part of the assigned radio spectrum is not or hardly used, or only used locally or at particular moments, while other parts are overused or in danger of being overused. More dynamic sharing of spectrum could be a solution to ensure sufficient availability in the future, by enabling more efficient use of the radio spectrum.

As a first step it is important to determine in which situations, with what concepts, users and user groups, technologies and under which conditions this could work best. The results would shape the position for next steps in the realm of Dynamic Spectrum Management (DSM) and Dynamic Spectrum Sharing (DSS).

This report provides the result of a study and an advice on the most feasible concept(s) and technologies that can be the starting point for more advanced, more dynamic and smarter approaches to spectrum sharing and related spectrum management. As spectrum sharing and the related management approach are usually tied together strongly, this report will only refer to dynamic spectrum management as a separate subject for those cases where this is relevant.

The scope of the study excludes sharing by a single operator (e.g. sharing of different protocols and techniques like 4G and 5G in the operator's own licensed band), as well as sharing between unlicensed users, but only includes sharing by two or more distinct end-user or user groups, with different spectrum use rights (one of which can be "unlicensed") in the same frequency band. The study provides a recommendation on the most realistic feasible concept(s) and technologies for concrete sharing applications, for instance to conduct a pilot or establish a test set up.

1.2 Study questions

The study answers the following questions, as posed by the Radiocommunications Agency:

1) Which concepts of dynamic spectrum sharing are promising for concrete application(s) (potential pilots, trials and/or 'proof of concepts')? Please, be specific and concrete, and provide a substantiated 'ranking' (f.i. in terms of spectrum efficiency, feasibility / realistic for pilots).
    a. For which type(s) of users (or user-groups)? It concerns at least of two users/groups, who are assigned different 'rights of use' (like primary vs secondary or licensed vs license free. It is not needed to elaborate a scenario with only license free applications).
    b. Which (existing) radio systems/applications are appropriate for dynamic spectrum sharing?
    c. Which basic techniques and methods (for instance AI (Artificial Intelligence), sensing, DSS within cellular networks, database) lend themselves for dynamic sharing and why?
2) In which frequency band(s) could the concepts you identified be tested and applied and why?
3) Which arrangements, rules, boundary conditions are needed for this?
    a. Technical protocol level: which arrangements, rules and/or standardisation can be applied or is needed for communication between radio-systems or with a central system (if needed)?
    b. At the user level: which (standardised) arrangements and rules can be applied or are needed with or between end users?
    c. At radio technical level: what has to be defined in the area of transmit and receive characteristics (a.o. power, duty cycle, transmitter and receiver characteristics)?

1.3 Principal and contractor

The study has been requested by Agentschap Telecom (Radiocommunications Agency Netherlands), part of the ministry of Economic Affairs and Climate policy of the Netherlands. The Agency has accompanied the study with a team that followed and supported it.

The study has been executed by Stratix B.V. in collaboration with prof. em. Ignas G.M.M. Niemegeers of TU Eindhoven, the Netherlands and Fred Goldstein, a consultant of Interisle Consulting in the USA.

1.4 Context

The need to engage in spectrum sharing varies over countries, due to legacies and differences in national policies. In comparison to most countries, the USA has a far higher proportion of radio spectrum in use by its defence forces, for instance. As a result, the more pressing scarcity induced early actions in the realm of (dynamic) sharing.

At the other extreme there are sharing concepts which address areas lacking radio-infrastructure. There is an obvious tension between assigning nationwide spectrum licenses or reserving entire bands for certain specific usages with actual intense usage in only limited areas or parts of a country. High intense usage occurs in relatively few specific sites like dense urban areas, specific industrial or (transport) logistics sites and in so-called 'hot-spots' with a large, heterogenous number of radio technologies and daily or even peak hour visitor numbers from 50.000 to several hundreds of thousands and/or with very large numbers of IoT devices. Some typical examples of these hot-spots are:

- Logistics hubs, such as large airports, main railway stations, metropolitan (public) transport arteries, and seaports;
- Dense central business districts and large university campuses or academic[1] hospitals;
- Event locations: convention centres, sports stadiums & concert venues as well as temporary outdoor event locations (festivals, national holidays, mass demonstrations);
- Very temporary hot spots due to calamities and emergencies.

Another type of hot-spots are area's where the problem is not the intensiveness of frequency use as such, but more the area related complexity of frequency allocation, specifically for (secondary) users that due to the frequency complexity have less options to choose from. Examples are area's near (one or multiple) country borders, or near multiple radar sites or radio astronomy sites, in particular when combined with large outdoor events.

Of course the combination of intense usage and complexity of frequency allocation may also occur, leading to additional challenges.

1.5 Approach

In this study the core question is to assess concepts for dynamic spectrum management and sharing, frequency bands and (policy) arrangements needed for this. The assessment is done by performing a review of academic and industrial lab research as well as concepts and technologies that are nearing proof-of-concept, pilot or trial ready stage or are already deployed on a limited scale in other countries. The study also identifies the frequencies and bands most mentioned as (most appropriate) target bands for specific sharing concepts and describe the (policy) arrangements.

[1] This is also true for other hospitals, but in particular in academic hospitals the number of persons and machines using radio spectrum is high and there is a higher diversity of used technology and innovations with regard to wireless technologies.

As such the study has a strong exploratory nature. However, the request to conclude with a 'ranking' in terms of spectrum efficiency and in particular feasibility and realistic for pilots, draws on findings for the second and third question too, in order to identify promising technologies and concepts. A ranking can also be linked to bottlenecks currently experienced or expected by end users and user groups in the Netherlands, or inferred from findings in other countries.

To address the questions a survey of the recent academic literature was conducted, a review of the situation with regard to the introduction of spectrum sharing policies and arrangements for various frequency bands around the world is conducted and the study is complemented by a set of interviews spread over academic researchers involved with radio technologies, developers of sharing systems, developers of (new) radio-technologies and chipsets as well as a select group of end users and experts.

Several interviewees have been selected who need to operate or develop sharing solutions for use in these hot-spot realms.

1.6 Scope of the assignment

The scope of the study is constrained by two boundaries:

1. no single operator (internal) sharing;
2. no sharing of a band between multiple license free technologies (e.g. co-existence of Bluetooth and Wi-Fi which both use the license free ISM-band of 2.4 GHz).

The excluded areas are depicted below in the five level scheme of the Wireless Innovation Forum (WInnForum) on spectrum sharing policies as Level 0 – Exclusive Use Spectrum, and Level4B – Unlicensed Pure Spectrum Sharing.

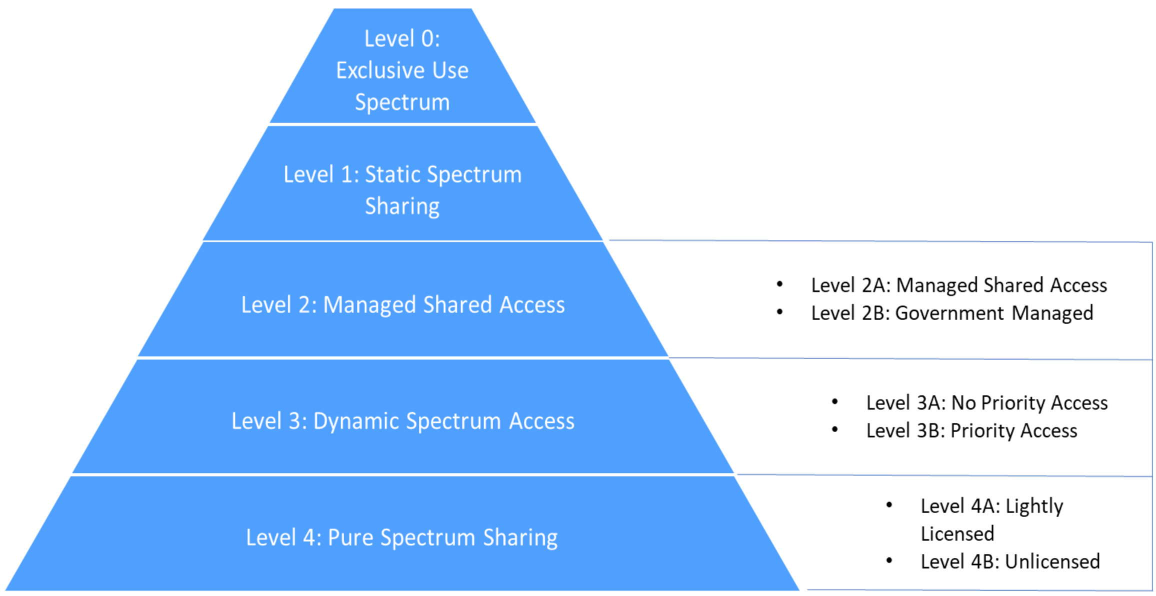

Figure 1: Five levels of spectrum sharing policies (Pucker, 2020)

The study focuses on technologies that allow for spectrum sharing between licensed and unlicensed uses, satellite and terrestrial, primary (incumbent) and secondary licensees as well as so-called opportunistic use of unused spectrum, which occupy predominantly level 2, level 3 and level 4A in the WInnForum scheme.

1.7 Readers guide

In Chapter 2 we provide an overview of our review of the current state of the art of the academic and scholar literature on (new) concepts and approaches for Dynamic Spectrum Management & Sharing. This study is complemented by a separate Annex document (Annex F), that provides a more detailed description of these concepts.

Chapter 3 presents the results from a desk research review of policies for Spectrum Sharing around the world, based on regulator websites and presented at industry conferences in 2020. We focus primarily on the main findings for Europe and North-America, but we also list some dynamic sharing policies concern deployment in Asia, Africa and Latin-America. Detailed descriptions are presented in the Annex.

In Chapter 4 we introduce a taxonomy for dynamic spectrum (management) & sharing, which we will use to classify the concepts found, as well as a set of properties and capabilities we use to arrive at a substantiated ranking of these concepts.

Chapter 5 covers the stakeholder side, and provides our main findings from the interviews conducted with a slate of eight interviewees, academics, manufacturers, developers and end users.

In Chapter 6 we provide a synthesis of the main findings of the former chapters to create a matrix of concepts and various technologies, methods and approaches with our ranking of feasibility to determine the most promising approaches, in order to provide an answer to the study questions.

Annex A describes the Ranking matrix used to assess spectrum sharing technologies;

Annex B contains a Glossary of abbreviations used;

Annex C gives an overview of references used;

Annex D gives an introduction of Spectrum sharing based on 5 levels defined by the Wireless Innovation Forum;

Annex E summarises the results of the interviews held;

Annex F gives details of some examples of existing Dynamic Spectrum Sharing arrangements;

Annex G provides a more detailed view of the advanced technologies which can contribute to spectrum-sharing.

2 State-of-the-art of Dynamic Spectrum Sharing

2.1 Introduction

In this chapter we give an overview of the state-of-the-art of Dynamic Spectrum Sharing (DSS) in the scientific and technical literature. We examine DSS methods and techniques from a number of perspectives.

Our overview, given the time and budget constraints, does not claim to be exhaustive. Based on the literature, we concentrated on what we consider as the most significant developments. We intentionally did not consider spectrum sharing between different radio technologies within the same organisation, e.g., the sharing of 4G spectrum with 5G, as is done for the introduction of 5G by some MNOs, awaiting the acquisition of dedicated 5G spectrum (e.g., 3.5 GHz). The systems and technology required for this, usually also called DSS, is part of the offerings of the major telecom equipment providers such as Ericsson, Nokia, Huawei, Samsung, etc.

In section 2.2 we develop a typology to characterise and put into perspective the different DSS methods. Such a worldwide accepted and used typology is not yet available. Furthermore, there are no generally accepted benchmarks to evaluate and compare different sharing methods.

In particular, for the efficiency of spectrum sharing, there are no metrics defined, and the scenarios in which they should be measured are unclear. When we talk about efficiency of spectrum sharing, we will use it in an informal way, to qualify to what extent a method does not waste opportunities to let sharing users have access to spectrum, they are entitled to and that is in principle unused, provided demand for spectrum is present. Waste and hence lower efficiency could occur, e.g., due to overhead spent on sensing, listen-before talk procedures, querying databases, over-sensitive receivers that cause false detection of primary users, etc.

It should be clear that many questions concerning the performance of different methods are not answerable at this stage, because not enough results from research, and experience, based on prototyping or pilot projects, are available. Therefore, for many aspects, only qualitative and no quantitative assessments can be given.

In the next Section, 2.3, we review currently used technologies as well as developments which will play an increasing role in future dynamic spectrum sharing. We refer to Annex F to some real-world examples of spectrum sharing concepts, and to Annex G for more detailed descriptions and discussion of the supporting technologies from Section 2.3.

2.2 Defining characteristics of DSS concepts

There is, at present, in the literature no generally accepted framework or typology to classify the different methods of dynamic spectrum access. We therefore use a set of, not always orthogonal, characteristics of DSS methods, based on elements used in the literature we consulted for this study such as :

- The five levels of spectrum sharing policies of WInnForum as described in section 1.6.
- The taxonomy of Spectrum Access Models by Buddhikot as described in section 4.1.
- And for the literature study in particular, three recent textbooks on the subject of dynamic spectrum sharing (Elmasry, 2021 , Papadias et al., 2020, and Liang, 2020).

While WinnForum and Buddhikot focus on one specific characteristic (degree of exclusivity of spectrum use) to classify different types of spectrum access, several characteristics can differentiate the methods used for spectrum sharing and the related spectrum management. The main characteristics of DSS methods and related Dynamic Spectrum Management methods we consider in our scientific and technical literature study are authorisation regime, spectrum access policy and spectrum usage status acquisition. Each of these characteristics can be used for one or more spectrum sharing methods, as described in the following paragraphs.

2.2.1 Authorisation regime:

2.2.1.1 Licensing

We consider three groups of DSS license types, with specific examples for each group:

(1) *Licensed spectrum* sharing, where all users must have an authorisation to use the spectrum (often with different levels of authorisation):

- TV-White Space, as used in the US (TVWS)
- Licensed-Shared Access (LSA)
- Evolved Licensed-Shared Access (eLSA).

(2) *Unlicensed spectrum* sharing, where spectrum can be used without license, provided certain technical requirements are met:

- Licensed-Assisted Access (LAA), Enhanced LAA (eLAA) and Further-enhanced LAA (FeLAA)
- MulteFire
- 5G NR-U sharing

(As mentioned in section 1.6, this type of sharing is outside the scope of this assignment.)

(3) *Mixed licensed and unlicensed*, where some users are granted licenses and others do not need a license but have lesser access rights and are subject to more restrictions:

- Citizens Broadband Radio Service (CBRS)
- Dutch PMSE use in TV-White Space

Annex F provides a detailed description for a number of specific use cases for each of the above.

2.2.1.2 User hierarchies

A user hierarchy can define different user classes, corresponding to different levels of rights and protections

- Single level: e.g. sharing among unlicensed users (out of scope for this assignment)
- Two level: e.g., Primary Users (PUs) and Secondary Users (SUs)
- Three-level: e.g., incumbent, licensed and unlicensed general access users
- Multi-level: more fine-grained distinction between priorities in accessing spectrum

2.2.1.3 Radio technologies as base for authorisation

- Single technology, e.g., only 5G NR allowed
- Multiple technologies, e.g., Wi-Fi and LTE both allowed
- Technology agnostic, e.g., DARPA SC2 where any technology is allowed, within the technical constraints

2.2.2 Spectrum access policy

The spectrum access policy controls the spectrum sharing, and the eventual prioritisation (rights of use) in case of hierarchical sharing. Possible categories are:

- Concurrent spectrum access (CSA)

  SUs and PUs are transmitting concurrently on the same shared spectrum.

  The SUs are obliged to control their interference with the PUs to be at an acceptable level, so as to protect the PUs. This requires a method to predict the interference SUs will cause at the PUs, to decide whether concurrent transmission is permissible.

  CSA is also referred to as *spectrum underlay*.

- Opportunistic spectrum access (OSA):

  SUs temporarily use the shared spectrum without interfering with PUs by configuring their carrier frequency, bandwidth and modulation scheme to transmit on so called spectrum holes, i.e., frequency bands where the PUs are temporarily not active. When an SU detects PU activity, the SU stops its transmission. This requires a method to know the state of spectrum usage by the PUs.

  OSA is also referred to as *spectrum overlay*.

- Cooperative transmission:

  Networks share frequency bands relying on distributed cooperative techniques and/or a centralised DSA decision-making process.

  Methods used for cooperative transmission among users using the same radio technologies are similar to the ones used for medium access control for users in single networks. Some examples are:

  - *Time division multiple access* (TDMA), where multiple synchronised users share the same frequency band cooperatively in different time slots
  - *Frequency division multiple access* (FDMA), where multiple users share the same frequency band cooperatively in different frequency sub-bands
  - *Carrier sense multiple access* (CSMA), where nodes sense if the carrier is busy and only transmit if the carrier is available. This is also called *listen-before-talk* (LBT). A more general form of spectrum sensing and LBT can also be used more technology agnostic approaches (see the next paragraph).

2.2.3 Spectrum usage status acquisition

- Geolocation database of PU and SU scheduled activities:

When the PU's activity is regular and highly predictable, and can be shared with the SUs, the geographical and temporal usage of the shared spectrum can be recorded in a central database. If an SU wants to transmit on the shared spectrum, without interfering with the PUs, it first has to determine its own geographic coordinates and then consult the geolocation database for a list of frequency bands that are not used by PUs in the SU's location.

In paragraph 2.3.1. different approaches for database-driven solutions for spectrum sharing are described.

- Spectrum sensing:

Spectrum sensing can be done periodically or continuously, by SUs, spectrum sensors, or even involving a dedicated sensing network. It can be done by each sensing device individually or in a cooperative way by combining the readings of multiple sensing points to improve the sensing accuracy.

The spectrum-usage characterisation can have different levels of sophistication.

Good spectrum sensing should have a high probability of detecting the presence of signals that should not be interfered with and a low probability of false alarm. However, there is a trade-off between those two metrics: usually, increasing the probability of detection to better protect primary users, is achieved at the expense of increasing the probability of false alarm, leading to less spectrum access opportunities. Spectrum sensing is an active research area.

In paragraph 2.3.2 different approaches for spectrum sensing centred solutions for spectrum sharing are described.

- Beaconing:

Status information about spectrum usage can also be conveyed by messages broadcast by beacons, on the basis of which non-primary users can plan their transmissions to avoid interference with the primary users. This requires a beaconing infrastructure, e.g., transmitters next to radar stations, operating on a control channel (Labib et al., 2017).

2.3 Techniques used for sharing

Among implementations of spectrum sharing, several different techniques are used, with varying degrees of success or pain.

2.3.1 Database-driven

Some sharing arrangements are driven by a database, requiring devices to query it in order to get permission to transmit on certain frequencies. The arrangement can be passive (only retrieve information from the database) or active (also enter a reservation into the database, so that another secondary user knows that it cannot use that frequency at that location and time).

TV White Space and the pending 6 GHz Standard Power are shared using a daily query, providing their geographic coordinates to a server that uses government-sanctioned models to compute exclusion zones or interference criteria. CBRS queries to the Spectrum Access System (SAS)[2] are no more than five minutes apart, creating near-real-time control over devices.

At least one manufacturer of 5 GHz equipment supports access to the U-NII-2[3] portion of the band where Terminal Doppler Weather Radar (TDWR) needs protection via its own database. The devices, which include geolocation, query the server at installation and determine which frequencies, if any, must be protected at that location. Thus no more than 60 MHz of the 80 MHz that could be barred for TDWR is actually barred, and no barring occurs more than 35 km from a TDWR site.

In some arrangements, not all devices need to access the database. Very low power devices may be exempt, and client devices may be controlled by a local “master” node, which retrieves the relevant data from the database.

2.3.1.1 Propagation modelling

A key requirement of database-driven concepts is propagation modelling, so that the interference can be predicted in advance. Several different models beyond free space path loss are in use, none of which is actually expected to be particularly accurate, but which may have an associated margin of safety.

On top of the inherent inaccuracy of propagation models, fading effects make it impossible to predict exact levels at a specific time and place. Therefore, a probability function is used. Modelling for interference purposes must use a much lower probability threshold than modelling for coverage prediction (for instance: coverage prediction may be based on 95% time and location probability, while interference prediction is often calculated with 1% time and location probability).

One well-known model is the Okumura-Hata model, which is based on empirical observations of path loss in Japan taken by Okumura and converted by Hata into formulas. It has urban, suburban, and rural models that account for typical clutter in those environments. The Okumura-Hata model is often used for coverage predictions.

The original Hata formulas were intended for 150-1500 MHz; extended “eHata” models are often used on higher bands for distances below 1 km, and blended with another model (such as the Longley-Rice Irregular Terrain Model) between 1 and 80 km.

Several ITU models are also available, though not yet in widespread use for interference calculation purposes.

[2] See also paragraph 3.3.3 on CBRS

[3] US designation: U-NII-2A = 5250 - 5350 MHz, U-NII-2B = 5350 - 5470 MHz, U-NII-2C/2e = 5470 - 5725 MHz

Ideally, interference modelling should take into account the power sum of all interferers, rather than just a single interferer. However, most schemes only consider a single interferer, and add a sufficiently large safety margin. The CBRS scheme does use an additive approach.

The most difficult part of propagation modelling is clutter. Buildings and vegetation (primarily trees) are the major cause of path loss in most real-world networks operating on microwave frequencies. Clutter loss is extremely hard to forecast as it can vary widely based upon the height of trees and buildings along the path, or the exact location of one end of the connection. Modelling of potential interferers to protect incumbents thus generally takes an approach where clutter losses are minimised (worst case for interference), in contrast to how modelling of likely coverage generally takes an approach where higher clutter losses are assumed (worst case for reception).

2.3.1.2 Documentation listed by European spectrum sharing Database operators

During our desk research we encountered two European firms developing / operating databases for shared spectrum with various technologies (TVWS, LSA, CBRS): Nominet from the UK and Fairspectrum from Finland.

Nominet UK is the operator of the UK country code Top Level Domain of the Domain Name System. However, a recent press release (2 October 2020), informed the public Nominet UK has sold its spectrum database operations to RED Technologies (Nominet, 2020).

We have encountered several mentions of Nominet as being a TVWS database provider in a number of countries. Nominet UK also had entered the US market as a CBRS database service provider.

Fairspectrum is a start-up who has worked in Horizon 2020 project Coherent. They have not only developed a TVWS databases for dynamic spectrum sharing, but trialed/piloted LSA in a number of countries, including the Netherlands (Fairspectrum, 2016). This was an LSA sharing trial with the Dutch Radio Agency in the 2.3 GHz band to test sharing this band with wireless video-cameras.

We found a number of recent papers by Fairspectrum, indicating they have (tried) to evolve and expand their LSA database.

Licensed Shared Access evolution enables early access to 5G spectrum and novel use cases (Yrjola & Kokkinen, 2017), published in a trial of Fairspectrum and Nokia, is as far as we can see, geared toward the Finnish situation in the 3.4 – 3.8 GHz, where 3 x 130 MHz is allocated for mobile operators with 'secondary sharing' supported by LSA. They name it *evolved LSA* and it might be a pre-standard version of eLSA.

Licensed shared access field trial and a testbed for satellite-terrestrial communication including research directions for 5G and beyond, published on 20 November 2020 in the *International journal of satellite communications and networking*, funded by a grant of the European Space Agency, is focused on spectrum sharing between IMT and Satellite Downlinks.

In the paper they mention they used a simplified version of the CBRS spectrum access system (CBRS SAS) - CBRS devices protocol. The paper provides a far more extensive listing of parameters used and protocols for information exchange, than ordinarily encountered.

2.3.2 Sensing

Sensing is used in many sharing arrangements.

Sensing can be deployed in each end-user device, only in a "master" device which controls the other devices, or in a separate network of receivers.

2.3.2.1 Spectrum-sensing metrics

- Energy detection

In energy detection spectrum sensors integrate the sensed power spectral density in over the sensing time period. This is the simplest spectrum sensing metric and is widely used for that reason.

- Time, frequency, and power sensing.

  This spectrum technique focuses on detecting the presence of signal energy on certain frequency bands, based on factors such as time intervals and signal power measured within a frequency band.

- Signal characteristics

  With this spectrum sensing technique, the sensor attempts from sampling, to estimate the sensed signal to find specific details about it. When the radio technology used by the PU is known, the sensor can perform more signal-specific spectrum sensing techniques such as waveform-based spectrum sensing or cyclo-stationary sensing. This technique requires receiver-like sensors and signal processing[4].

- Space-based detection

  This consists of sensing spectrum usage as a function of the angle-of-arrival of the signal to the sensor, e.g., in case beamforming antennas are used.

And there are even more different variations possible, as shown in the table in Figure 2 (Vartiainen et al. 2016; Strickling 2011).

[4] And some form of coordination in case of multiple secondary users, possibly manual (for short range devices)

Stratix

TABLE I. RECENTLY PROPOSED AND STUDIED SPECTRUM SENSING METHODS.

Ref.	Method name	Operational principle	Weakness	Performance
[22]	LAT CSS protocol	Sense&access spectrum simultaneously with the assistance of full-duplex techniques	Transmit power-throughput tradeoff	Outperforms LBT when SU Tx power is low
[23]	Savitzky-Golay smoothing	Smoothing	SNR> -10 dB	Reducing noise, better than standard linear moving average method
[24]	Cooperative sensing	Combat shadowing&fading, mitigate impact of noise uncertainty & SU interference?		Outperforms convential CSS methods for noise uncertainty and interference
[25]	Joint-SAMP CSS	Sparsity adaptive recovery algorithm	Max. 15% of the channels can be occupied	Outperforms JD, SOMP and GSP joint detection algorithms
[26]	TS CSS	Including PSO algorithm, m maximize the energy efficient		Energy efficiency better compared to single-stage CSS
[27]	LINWPSO CSS	Optimal weight setting	Computational complexity	Better CROC performance than MDC and SNR based methods
[19]	ED based sensing		SNR> -13 dB to get $P_d >= 0.9$ (DVB-T signal)	Simple&efficient
[18]	WE based sensing	Wavelet entropy estimation, based on WT	SNR$>= -9$ dB Only low-frequency band	Lower computational complexity than WPE, cost effective, robust against noise uncertainty
[18]	WPE based sensing	Based on WPT	Only low-frequency band	Low computational complexity, when SNR> -6 dB, WPE=WP detection performance
[28]	Energy ratio algorithm	Detecting appearance of PU	Only for OFDM based CRs	Improved the performance in the secondary network throughput, high immunity to frequency-selective fading, complexity 2*ED
[21]	Single user multi-threshold	Based on phototropism	Defining required distribution	Reduced the overall probability of error, improved detection performance compared with classic ED, MF and cyclostationary detection
[20]	ED to CAV	Coarse & fine sensing	Longer sensing time than TSS	Accurate detection of noise power, better than ED to MME
[20]	ED to MME	Coarse & fine sensing	Longer sensing time than TSS	Accurate detection of noise power
[29]	Sensing method CSS	Rewards truthful and accurate reporting, distributed		Reduces the effect of spurious reputation values

LAT=listen-and-talk
CSS=cooperative spectrum sensing
LBT=listen before talk
SAMP=sparsity adaptive matching pursuit
JD=joint detection
SOMP=simultaneous orthogonal MP
GSP=generalized MP
TS=two stage
PSO=particle swarm optimization
LINWPSO=near inertia weight particle swarm optimization
CROC=complementary receiver operating characteristi
MDC=modified detection coefficient
ED=energy detection
WE=wavelet entropy
WT=wavelet transform
WPE=wavelet packet entropy
WPT=wavelet packet transform
OFDM=orthogonal frequency division multiplexing
TSS=two-stage sensing
MME=maximum-minimum eigenvalue detector

Figure 2: Table evaluating sensing methods from Vartiainen, Höyhtyä, Vuohtoniemi, & Ramani. (2016).

2.3.2.2 Compromises in receiver design

The design of the receivers is crucial for any form of sensing. Very sensitive receivers, and receivers which can evaluate many of the metrics mentioned above, are either very expensive or have bad inter-modulation performance and therefore false detections. For some solutions cheaper receivers can be used, for instance by allowing for a longer integration time. A proper balance has to be found, to find a usable optimum between costs and speed, flexibility and ultimate efficiency of a dynamic spectrum sharing solution.

2.3.2.3 *Examples of arrangements using sensing*

For the US, a "TV White Space" portable/mobile device, such as a wireless microphone, whose power is limited to 50 mW/6 MHz, may employ sensing in lieu of a database lookup. However, no devices appear to have actually been approved on such terms.

On the US CBRS band, sensing is handled by the networks of Environmental Sensing Capability (ESC) receivers. These are specialised devices attuned to specific radar patterns, pointed at sea. The ESC securely reports its findings to the affiliated SAS, which in turn requires a sufficient number of CBRS Devices to vacate the impacted frequencies such that the aggregate interference is below the tolerated level. CBRS devices themselves do not perform sensing. The ESCs do, however, require protection themselves, in order to prevent CBRS usage from interfering with their radar detection functions, and thus each sensor essentially creates its own CBRS exclusion zone, protected by the SAS. ESC locations are not public and thus potential users do not find out about this until they attempt to register devices with the SAS.

The 3.65-3.7 GHz Wireless Broadband Service band, which was later subsumed into CBRS, required devices to use a contention-based protocol. Before the introduction of CBRS, the use of this band required sensing of other devices on the band, and fell into two categories. Devices which could only sense similar devices were authorised to operate on the lower 25 MHz; devices which could sense any device were authorised for all 50 MHz. No similar requirement applies to CBRS.

A major application of sensing is on the US 5 GHz U-NII-2 band. Radar detection in the United States is based on a series of tests, generally seen as more difficult than those used in Europe. Many 5 GHz devices, especially lower-priced ones, thus do not support the U-NII-2 (DFS) segment of the band. False detection is also a problem, as the crowded band randomly creates patterns that some devices detect as radar.

In none of these cases is sensing seen as a particularly successful. The FCC is considering opening the 3.45-3.55 GHz band for sharing. This is adjacent to CBRS and also has a mix of military applications. In its Notice of Proposed Rulemaking, the FCC has suggested that an informing incumbent model be adopted instead of sensing. This option would be warmly welcomed by potential users, and it would also be appreciated as a substitute for sensing on CBRS itself.

2.3.3 Synchronisation

Interference may be avoided or reduced by arranging for transmissions to be synchronised. An example of this is an agreement among some LTE users on CBRS spectrum to adopt certain TDD timing parameters, so that the base stations all transmit in synchronisation with each other and thus do not mutually interfere. Similar agreements are expected between some CBRS users and licensees of the adjacent 3.7-3.98 GHz band.

This synchronisation mechanism is not unique to spectrum sharing arrangements; the same mechanism is often used between licensed operators in adjacent geographical areas. For instance, see the recommendations from the GSMA for TDD LTE and 5G NR (GSMA, 2020).

A downside of this type of coexistence agreements is that they tend to limit flexibility and choice of technology. Moving, for instance, from 4G LTE to 5G NR is possible but only with specific timing arrangements. Different uplink/downlink capacity combinations also become problematic. And dissimilar technologies, such as OFDM-based symmetric point-to-point links, do not coexist well with LTE-based access links.

2.3.4 Localised Spatial spectrum sharing

Two transmitters using the same frequency can coexist (and received by different receiving counterparts), even in the same geographical area, if they create spatially constrained "beams" which can at some locations both be received, but still be distinguished by the receivers (differentiated by angle of arrival). 4G/5G and various Wi-Fi versions all use this principle to provide multiple parallel streams from a single network access point to the receiver (MIMO), but it is theoretically possible to use this mechanism to allow multiple networks to share spectrum within an area.

However, this is still to a large extent a research topic.

2.3.5 AI Techniques: Machine Learning (ML)

A lot of research is going on the application of AI to wireless communication and to dynamic spectrum management (DSM) in particular. Machine Learning (ML), based on deep learning, has turned out to be a powerful tool to perform system functions that otherwise would be too difficult, too computationally complex or not scalable.

Research on ML techniques for DSM has mainly been used for:

- spectrum sensing
- signal classification and traffic recognition
- spectrum-usage prediction
- dynamic spectrum access decisions.

However, there are very few practical implementations of ML for these purposes at this time.

2.3.6 Full-duplex (FD) Radio

The use of full-duplex radios, i.e., radios that are able to transmit and receive on the same channel concurrently, is, in principle, a powerful means to improve the efficiency of spectrum sharing.

However, there are still some issues with full-duplex radio, e.g., the higher energy consumption due to the signal-processing required for cancelling the self-interference.

In order to exploit the potential of full-duplex radio, in particular for spectrum sharing, a lot of research is still needed. On the other hand experimental research is taking place and the mechanism is being considered for future Wi-Fi standards.

2.3.7 Radio Virtualisation and Infrastructure Sharing

Network virtualisation and infrastructure sharing can support very efficient dynamic spectrum sharing, e.g., for allowing an MNO to provide spectrum as a service in evolved Licensed Shared Access (eLSA) to a vertical operator[5].

For example, one could allow a number of independent wireless networks using a single set of hardware to operate, in parallel and isolated from each other, sharing the same spectrum in a dynamic way.

An infrastructure provider could, for example, split its owned spectrum band into smaller chunks and lease it to verticals. Another possible example is for an infrastructure provider, instead of splitting its own spectrum into smaller chunks, to provide the common infrastructure which allows other operators to use their own spectrum bands.

It is a proven concept that has been prototyped and demonstrated successfully in the DARPA Spectrum Challenge. We expect that, given the pressure to significantly improve spectrum utilisation through

[5] Of course other solutions such as regional roaming also may provide more efficient use of resources, but they may have other disadvantages regarding coverage obligations, providing a level playing field etc.

dynamic sharing and the need to drive down infrastructure costs resulting from network densification, radio virtualisation will play a significant role in the future.

2.3.8 Blockchain and other Distributed Ledger Technology

The main idea behind blockchain (and other Distributed Ledger Technology or DLT) is to distribute the validation authority of transactions to a community of nodes and to use cryptographic techniques to guarantee the immutability of the transactions.

Blockchain could be used to reduce the administrative expenses of dynamic spectrum access systems and thus increase the spectrum efficiency. A lot of research is going on in exploring the opportunities using blockchain technology, for instance on how to use blockchain technology for CBRS (Yrjola, 2018).

The application of blockchain technology to dynamic spectrum access is still very much a research topic, however experimentation with blockchain is already happening, e.g., ANFR has started a pilot for PMSE[6] (OPSI, 2018). The ANFR solution aims to satisfy several features, offering a secure, transparent automated tool that can be used by both a central organisation management as well as a decentralised self-organised governance system, dependent on the frequency bands considered. Also it is aimed to be used over several countries, respecting the sovereignty of each country while facilitating collaboration. The blockchain technology appeared to be the answer to these requirements and also guarantees the integrity, the immutability, the transparency and the traceability of the reservations of frequencies. The current use case primarily involves PMSE use, but aims to pave the way for a future extension of the solution designed to manage

- cross-borders events, involving the participation of several national spectrum regulation authorities.
- non PMSE spectrum assignment issues so as to promote a real dynamic frequency sharing strategy across the spectrum range.

Through this solution, frequencies sharing among countries that raise sovereignty issues could also be addressed by creating a consortium and providing nodes. Each country of the consortium could therefore have the same accesses and share the same data, on servers based within their own organisation. ANFR is also developing a Software Designed Radio based spectrum organisation to complement the solution and allow connected objects to dynamically organise their spectrum occupation through the blockchain.

[6] https://blockchainfrequences.anfr.fr/, /

3 Dynamic spectrum sharing – policies & standards

In this chapter we provide an overview of desk research into a series of industry conferences and several websites of radio regulators and agencies, which we reviewed on recent consultations or notices of proposed rulemaking.

We will look in particular at the interplay between policies and various frequency bands, as well as what we could find about the arrangements, the parameters required to register and protocols.

We reviewed in particular the presentations from the following recent industry conferences on Dynamic Spectrum Sharing:

- WInnForum Online Three Day Deep Dive Event: Spectrum Sharing - Past, Present and Future, September 22-24, 2020 (WInnForum, 2020)
- Dynamic Spectrum Alliance Global Summit,
  November 3-5, 2020 - (DSA, 2020)

A number of the presentations, given by regulators and manufacturers, on these conferences provided us with pointers, links and references to follow through towards their websites.

We also followed through on documents filed by respondents in consultations, presenters mentioned conducting pilots or stated they offered systems to support (dynamic) spectrum sharing.

We list our findings along a set of spectrum sharing technologies encountered during our desk research for Europe, the USA and the rest of the world.

3.1 Roles of the ITU, WRC, EU, CEPT, FCC and other radio agencies

3.1.1 International Telecommunications Union/World Radio Conference

For this chapter we assessed policies and proposals in various regions of the world. Spectrum policy at a global level is coordinated today in the ITU-R (International Telecommunications Union – Radio division), which convenes World Radio Conferences, global coordinating meetings. Since 1948, the ITU resorts under the umbrella of the United Nations.

For (radio) regulation the ITU has divided up the world in three regions. Europe, Africa, the Middle-East and the former Soviet Union and Mongolia are Region 1, the America's and Greenland are Region 2 and the remainder of Asia and Oceania are Region 3.

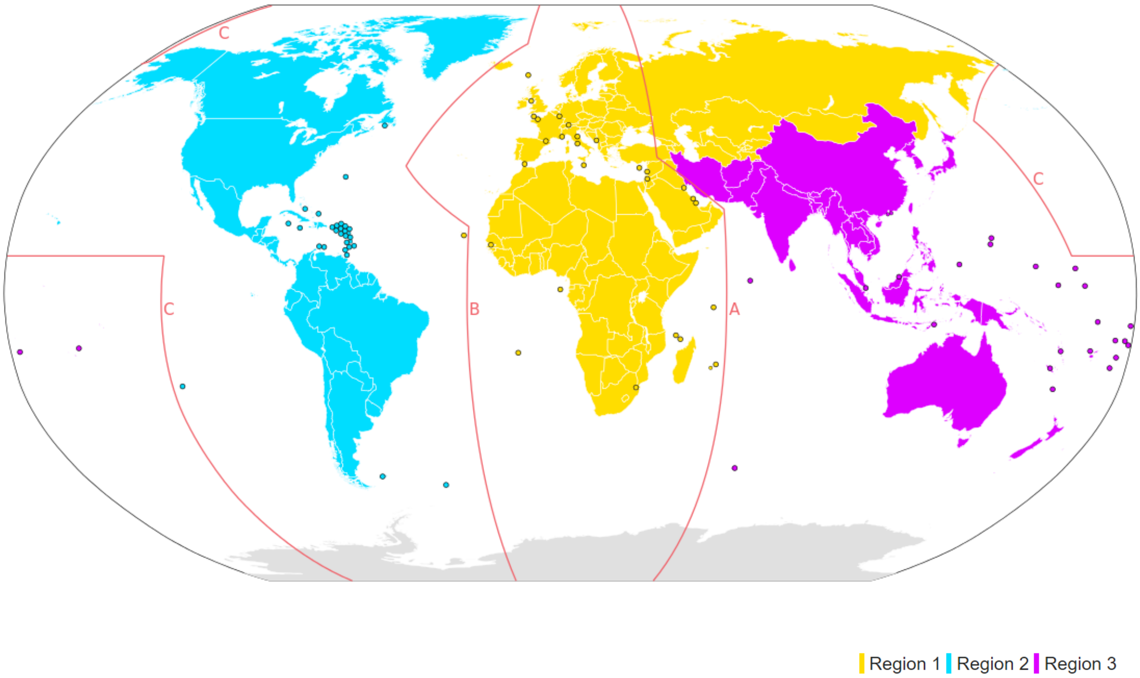

Figure 3: ITU Regions for (radio) spectrum regulation

The allocations of the frequency bands at high-level are coordinated at the World Radio Conference. However sometimes for (more or less) similar technologies and services one often encounters (slightly) different frequency bands between the Regions. This is mostly due to historical choices or economic, political strategical choices (or a combination of these factors). Within regions generally one organisation takes the lead in standardisation, such as CEPT in Europe and the FCC in North America. Paragraphs 3.1.2 thru 3.1.4 give an overview of the regions and the most important organisations involved in spectrum allocation.

Historically, significant technical differences existed at the level of standards between the regions. These differences began gradually to decline in the 1990s and 2000s. Today, quite a number of radiofrequency technologies are adhering to global standards, like LTE, 5G-NR, Wimax and Wi-Fi, but some of them do operate at different (partially overlapping) frequency bands per region.

Vendors however aim to produce chipsets, for the global market, often including bands which are only allowed in specific regions.

On one hand this is an annoying and sometimes costly inconsistency: equipment has to be designed an produced far more flexible towards spectrum use than would be necessary if the spectrum compartmentation was more strictly standardised worldwide. But on the other hand this actually works as an opportunity for introducing Dynamic Spectrum Sharing techniques in frequency bands not allocated for exclusive licensed 5G or Wi-Fi in a region, as another region effectively creates the mass volume market in capable chipsets that will make equipment affordable.

Also globally operating standards organisations, branch organisations as well as user organisations explore the opportunities of spectrum sharing and try to come up with effective standards or common practices. Examples of such organisations are given in paragraph 3.2.

3.1.2 Most significant in ITU Region 1: Europe/CEPT

The European Union and its predecessor the European Economic Community have in particular since the 1970s developed general (industrial) policies to use Standardisation and Harmonisation as a prime means to establish a European Common Market. Its objective has been to reduce the fragmentation of national standards and deliver economies of scale to manufacturers and developers of technologies.

Spectrum policy in Europe is harmonised by the EU and the Member States. In the EU the Member States coordinate their spectrum management approaches in a common regulatory framework to support the internal market for wireless services and to foster innovation in electronic communications and other sectors. The European Commission works together with Member States to modernise spectrum management to facilitate spectrum access through more flexibility in usage conditions.

At a Pan-European level and being one of the bodies within region 1 of ITU, the CEPT, established in 1959, is a coordinator for both Post and Telecoms in Europe. The current CEPT-membership consist of 48 countries, extending from the Atlantic to the Russian Federation. One of CEPT's three main branches today is the European Communications Committee. The CEPT website states (under "what we do"):

We use our expertise to reduce spectrum scarcity and improve sharing and access to spectrum to enable the introduction of new technologies, whilst protecting existing ones.

In Europe and on other continents the pressure to engage in (dynamic) Spectrum Sharing has been present, but less strong than in the United States. A major reason is the far larger "allocation footprint" in the USA of spectrum for military purposes. Despite that, however, spectrum scarcity is increasing too outside the USA.

Europe has allotted more spectrum to mobile operators than the USA, also, with higher population density over most of the continent, mobile operators tend to cover more rural area.

Around 2010 the EC started research to promote the use of shared spectrum resources in the EU (EC, 2020). This was called CUS, the 'collective use of spectrum'. An overview of technology neutral spectrum sharing protocols from 2015 can be found on the 'EU Science hub' (Fuehrer, 2012). The EC is assisted in the development of radio spectrum policy by a high-level advisory group, the Radio Spectrum Policy Group (RSPG).

The recent RSPG report on spectrum sharing reports a number of promising European spectrum sharing initiatives in the Czech Republic, Denmark, Finland, France, Italy, the Netherlands, Portugal and Slovenia(RSPG, 2021; RSPG, 2021).

In recent years a few European countries (UK, NL, SE, FR and DE) enabled 'Static Sharing (Level 1, in WInnForum terminology)' with private-GSM, private-LTE and now private-5G implemented with (lower power) picocells/microcells in the 1.8 GHz "guard band", 2.6 GHz band and now more and more countries opening some spectrum in the 3.5 GHz band for enterprises.

The opening of private 5G in several countries, in particular for enterprise / industrial users with local licenses has induced major vendors like Nokia to (re-)enter the Enterprise-market, effectively recreating a mobile equivalent of the old PABX-market.

Microwave links are often licensed via license assignment policies that can be categorised as "Static Sharing". The largest group of microwave link users are mobile operators for mobile backhaul. The policies for licensing an entire band (= Exclusive Use, Level 0) to a mobile operator or per-link licensing (Static Sharing: WInnForum Level 1) of microwaves differ per country.

Most sharing in Europe occurs in the unlicensed bands (unlicensed -unlicensed) which are outside the scope of this study. These technologies have proven so popular that 2.4 GHz Wi-Fi-users now often experience congestion in apartment buildings and dense neighbourhoods.

A specific market segment with existing sharing arrangements is Program Making and Special Events, which use TV whitespaces in the UHF as secondary users for a.o. wireless microphones, wireless instrument links and earbuds and various other devices in studios and on stages. However, the move from analogue towards digital terrestrial TV and the allocation of spectrum for mobile has significantly reduced the opportunities for secondary use in the UHF band.

The PMSE-sector has also spectrum needs for wireless TV-cameras. Trials have been conducted in the 3GPP band 40 (2.3 – 2.4 GHz) in several countries with sharing technique LSA (Licensed Shared Access) for the wireless video-camera segment including Finland, the Netherlands and Portugal in the years 2014-2019.

The UK radiocommunications agency Ofcom published a consultation document in 2015 that led to a framework for spectrum sharing(Ofcom, 2015). In 2019 Ofcom published a decision to support local connectivity requirements by opening up airwaves (spectrum) previously only available for certain services for shared use(Ofcom, 2019). Promoting spectrum sharing to foster innovation and removing bottlenecks in spectrum availability is becoming an integral part of the Ofcom strategy (Ofcom, 2020a; Ofcom, 2020b).

The French radiocommunications agency ANFR is also exploring innovations that will help to easy spectrum sharing. One example is their blockchain pilot mentioned in 2.3.8. Also the ANFR has taken part in Station F, the biggest global start-up campus located in Paris. This ANFR presence makes it possible to increase work with start-ups in the different strategic sectors where the use of frequencies is required[7].

An overview of different policies with regard to the PMSE sector in a number of European countries is described in a recent Stratix report commissioned by the Ministry of Economic Affairs and Climate Change (Stratix, 2021).

3.1.3 Most significant in ITU Region 2: USA / the Federal Communications Commission

While Region 2 comprises the Americas and Greenland, the economic clout of the USA provides it a leading role in Region 2 in setting standards and initiating developments.

The United States has largely adhered to a regime of exclusive uses of most of the radio spectrum, but as demand has increased, especially in the microwave range, sharing has become more common, and future spectrum management policies are much more attuned to sharing. In the United States, authority over spectrum is divided into two agencies. The National Telecommunications and Information Agency (NTIA), part of the cabinet-level Department of Commerce, is responsible for Federal spectrum, both civilian and military. The Federal Communications Commission (FCC), an independent agency.is responsible for non-Federal spectrum. More sharing between the two has been mandated by Congress, and the two agencies work together to meet that mandate.

Within the FCC's jurisdiction, sharing is also increasing, though incumbents routinely resist it. Spectrum has become a valuable commodity, with mobile telephone operators paying many billions of dollars at auction for their licenses, so any spectrum that can possibly be sold or leased to the mobile carriers is seen as a potential financial asset. Even spectrum that is not being used by its licensee is treated as potentially valuable for some future buyer. This transition of spectrum, from efficient use to financial vehicle, affects spectrum policy in general, and should be kept in mind when sharing is evaluated.

A Table of Allocations maintained by the FCC is largely but not entirely consistent with the ITU equivalent. It specifies which spectrum is Federal, non-Federal, and shared between the two categories, and which category of service is assigned to each. A service (such as Fixed, Fixed Satellite, Broadcasting, Radiolocation, or Mobile) may then be designated as primary or secondary in that spectrum, with secondary users required to protect primary ones.

[7] https://www.anfr.fr/fileadmin/mediatheque/documents/Publications/ANFR-brochure-innovation-EN.pdf

Sharing in the USA comes in different forms. Besides federal/non-federal, it can be licensed-licensed, licensed-unlicensed, or shared between different types of unlicensed use. Under US rules, all licensed services take precedence over unlicensed. Licensed services typically share spectrum on a non-interference basis, often geographic. If spectrum is being transitioned from one licensed use to another, incumbents are generally protected until they can vacate.

Unlicensed use at very low power is in general accepted over a wide range of frequencies. The FCC specifies 65 Restricted Bands, ranging from very specific channels (e.g., 6.26775-6.26825 MHz) to wide bands used by sensitive applications (e.g., 3600-4400 MHz, used by satellite downlinks, and all radio frequencies above 38.6 GHz where unlicensed use is not otherwise allowed). Outside of those bands, low-power intentional radiators, such as garage door openers and wireless microphones, may operate. But most unlicensed operation is on specifically defined bands where higher power levels are allowed.

Amateur radio operation takes place on frequencies both shared and unshared, often shared with federal use, with the understanding that licensed radio amateurs are responsible for protecting certain other types of operation, and may have to vacate spectrum when asked.

The US National Institute of Standards and Technology (NIST) is also addressing several research spectrum sharing topics(NITS, 2019).

3.1.4 ITU Region 3 and radio agencies in other countries in ITU Regions 1 and 2

In Region 3 Japan had a major role as communications technology developer, standards setter and market volume creator in the past. Since the turn of the century, however, South-Korea, China and Taiwan have developed very sizable communications electronics & chipset development and production industries.

In the run up to 2000 with 3G there was still an attempt by Qualcomm of the USA, Japanese firms, China and Europe to develop different, competing technologies. When Japan then chose the same technology standards as Europe (Wideband-UMTS), it became clear that the era of 'national champions with different technologies' was over. Today whether it is 3GPP with LTE and 5G-NR, IEEE with Wi-Fi, or the Bluetooth consortium, global mass market volume is a key factor.

Standard wars between competing technologies do still occur occasionally[8], but in general the market for technologies is now global in scope and size. Radar technology is still different, as radar detects and processes its own signal.

Where in the domain of mass market technologies, vendors producing chipsets set the trend, it is in the realm of central systems for dynamic spectrum sharing and in particular launching initiatives for the IT in Spectrum Access Systems / Spectrum Brokers and allocating frequency bands, where national radio regulators / agencies still have some serious policy space. This also applies also to decisions made by regulators in countries like Canada, Australia, Africa or Latin-America in their central spectrum systems.

However, policy makers will have to be careful about introducing technologies/protocols that need to be implemented by the large volume chipset producers. While the market for Dynamic Spectrum Sharing is closely linked to the one for Software Defined Radio / Cognitive Radio, without chipsets available that have the hardware to operate at the desired/envisioned frequencies for DSS, chances will be low for development at affordable, competitive prices.

[8] A recent example is in Car electronics (C-ITS) where an LTE-based standard competes with an IEEE-developed standard.

3.2 Standards groups and interest groups

Several standardisation groups recognise the growing importance of spectrum sharing and developing standard solutions for spectrum sharing and are briefly described in this paragraph, along with some relevant interest groups.

3.2.1 3GPP

3GPP, the worldwide standardisation body that provides the standards for mobile networks, states that Dynamic spectrum sharing (DSS) provides a migration path from LTE to 5G NR (New Radio) the new radio access technology for the 5G (fifth generation) mobile network by allowing LTE and NR to share the same carrier. DSS was included already in Rel-15 and further enhanced in Rel-16 (3GPP, 2020).

3.2.2 ETSI

ETSI is a European Standards Organisation, mandate by the EU to develop standards dealing with (among others) electronic communications. ETSI defines the "essential requirements" of the R&TTE directive in EN 300 220, including sharing enabling technologies such as LBT, low duty cycle transmission, and FHSS for interference avoidance.

ETSI also defines architectures and functional requirements for information exchange between license holder and secondary users in LSA/eLSA schemes (TS 103 652).

In addition, ETSI has reported on spectrum sharing in various technical reports (TR 102 970, TR 102 682, etc), but these do not have any normative status. For spectrum sharing in the 6 GHz band (Wi-Fi 6E), ETSI has recently drafted TR 103 631.

3.2.3 IEEE

In 2015 the IEEE published an overview of LTE spectrum sharing technologies (Ye et al., 2016). A number of IEEE standards support inter-technology spectrum sharing (Voicu et al., 2018), as is illustrated in Table 1.

Table 1: Literature review of inter-technology spectrum sharing with low-traffic technologies in a spectrum common (Voicu, Simic & Petrova, 2018

Technologies	Coexistence Goals	Performance Evaluation		
		method	metric	network size
Wi-Fi/ IEEE 802.15.4 [93]–[102]	*Impact on Wi-Fi* –**(implicitly) vs. standalone** [93], [96]–[99] *Impact on IEEE 802.15.4* –**(implicitly) vs. standalone** [94]–[98], [100]–[102] *Other* –**Wi-Fi packet error rate below 8%** [99] –**solve performance degradation of 802.15.4** [100]	–**measurements** [93], [95]–[98], [100]–[102] –**analytical** [94], [99] –**simulations** [94], [100]	–**throughput** [93], [94], [96] –**packet error rate/loss** [93], [95], [97]–[99], [102] –**packet delivery ratio/success rate** [100]–[102] –**received power** [101] –**channel power** [98] –**SIR** [98] –**delay** [100]	– **1 link of each technology** [93]–[97], [100]–[102] – **1 Wi-Fi link & several 802.15.4 devices** [98], [99] – **100 802.15.4 devices and abstract interference** [100]
Wi-Fi/Bluetooth [96], [103]–[110]	*Impact on Wi-Fi* –**vs. standalone** [96], [103]–[105], [108], [109] –**vs. coexistence without additional spectrum sharing mechanisms** [106], [107], [110] *Impact on Bluetooth* –**vs. standalone** [96], [103]–[105], [109] –**vs. coexistence without additional spectrum sharing mechanisms** [106], [107] –**vs. other coexistence mechanisms** [107]	–**measurements** [96], [103], [104] –**analytical** [108] –**simulations** [104]–[107], [109], [110]	–**throughput** [96], [103], [104] –**packet error rate/loss** [103], [105], [107], [109], [110] –**delay** [106], [107] –**jitter** [107] –**goodput** [106], [107] –**bit error probability** [108]	– **1 link of each technology** [96], [103], [104], [108]–[110] – **1 Bluetooth link & up to 2 Wi-Fi links** [107] – **up to 10 Wi-Fi devices and several Bluetooth links** [105], [106]
IEEE 802.15.4/ Bluetooth [95]	study mutual impact on both technologies (implicitly vs. standalone)	measurements	packet loss	two Bluetooth links and one 802.15.4 link
IEEE 802.15.4/ microwave oven [95]	study impact on 802.15.4 (implicitly vs. standalone)	measurements	packet loss	one 802.15.4 link and one microwave oven
Bluetooth/ {WCAM, RFID, microwave oven} [103]	study impact on Bluetooth vs. standalone	measurements	data rate, packet error rate	one Bluetooth link and one interferer of another technology
Wi-Fi/LTE D2D [111]	increase D2D throughput vs. different licensed/unlicensed spectrum use strategies	simulations	throughput	one Wi-Fi link and one multi-hop D2D flow
5G/IEEE 802.15.4 [112]	mitigate mutual interference vs. standalone & vs. coexistence with 5G without spectrum sharing mechanisms	simulations	throughput	one ZigBee and one 5G link
LTE/ZigBee [113]	study mutual impact between LTE and ZigBee vs. standalone	simulations	throughput, SINR	18 LTE BSs and 54 ZigBee APs
IEEE 802.15.4/any interfering signal [114]	detect collisions while transmitting	measurements	detection and false alarm probabilities	one 802.15.4 link and one 802.15.4 interferer

3.2.4 Dynamic Spectrum Alliance (DSA)

The Dynamic Spectrum Alliance (DSA) is a global, cross-industry, not for profit organisation advocating for laws, regulations, and economic best practices that will lead to more efficient utilisation of spectrum and foster innovation and affordable connectivity[9]. The alliance organises summits, produces reports on several related topics such as Automated Frequency Coordination (DSA, 2019a; DSA, 2019b) and is involved in several pilots[10].

[9] http://dynamicspectrumalliance.org/wp-content/uploads/2019/10/Enhancing-Connectivity-Through-Spectrum-Sharing.pdf

[10] See http://dynamicspectrumalliance.org/resources/ and http://dynamicspectrumalliance.org/pilots/

3.2.5 Whitespace alliance

The Whitespace Alliance aims to promote the development, deployment and use of standards based products and services as a means of providing broadband capabilities via WhiteSpace spectrum and Spectrum Sharing. By promoting the use of standards, the Alliance will enable companies to provide broadband connectivity at reasonable cost. The organisation also published a number of white papers and tutorials[11].

3.3 Examples of existing spectrum sharing arrangements worldwide

This section contains major examples of existing and evolving combinations of shared spectrum technologies and policies worldwide, sorted by frequency band.

3.3.1 European DVB band (470-698 MHz)

In Europe, the 470-698 MHz band is reserved for digital television (DVB-T/ DVB-T2).

High power broadcast applications are, by their nature, fairly inefficient in terms of spectrum use: the geographical distance at which a frequency can be reused is far greater than the distance at which a reliable service can be provided. As a result, there are large "white spaces" between transmission sites.

Use of DVB-T2 "single frequency networks" has improved efficiency, but there are still major white spaces which can be used.

Figure 4 provides an illustrative example (for DVB channel 21): the overlapping areas show three separate single frequency networks (plus one in Germany, in the bottom right corner). The areas between the marked areas are white spaces, which can be used for other purposes. The further from the marked areas a secondary user is located, the higher the transmission power which could be tolerated.

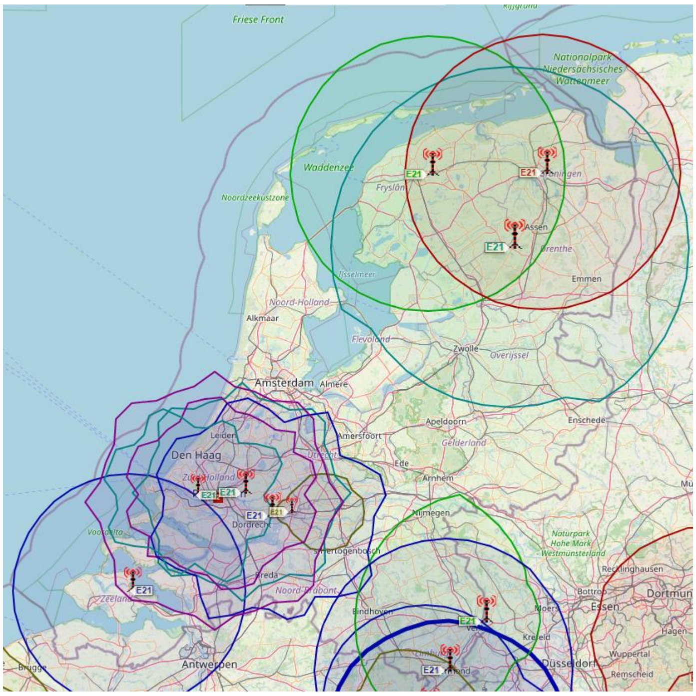

Figure 4: DVB-T2 coverage areas for channel 21 (source: fmscan.org)

11 http://whitespacealliance.org/WhitePapers.html.

In the Netherlands (and many other countries), PMSE users can use these white spaces, but with severe limitations on transmitted power. Also, they currently have to coordinate among themselves when operating in close proximity, as the Radiocommunications Agency only provides information about primary use in this band, not about other PMSE users.

3.3.2 ISM Bands

A number of bands are historically or currently used for Industrial-Scientific-Medical applications, primarily RF heating (including household microwave ovens). This application naturally generates serious interference to nearby devices, and as such that spectrum was deemed unusable for other purposes. While low-power ISM equipment is actually allowed on a wide range of frequencies subject only to a short prohibited list, power limits are higher on designated frequencies. ISM bands are thus shared mainly with unlicensed use, and in some cases with licensed use.

It was this sharing that gave rise to Wi-Fi, which began on the 2.4 GHz band, which is essentially the frequency band used for consumer microwave ovens. A similar allocation exists in the 5 GHz band (partially overlapping with the US U-NII band, mentioned in 3.3.5). In Region 2 (which includes the US), there is also an ISM allocation in 902-928 MHz.

The 902-928 MHz bands in the US are (partly) shared with Amateur use, which takes precedence and is allowed higher power. This is mainly an issue in the 902-928 MHz band, where Amateur FM repeaters typically operate at the band edges. Unlicensed devices, including broadband systems used by Wireless ISPs (WISPs), must protect them.

Also there is an ISM band from 24-24,25 GHz (see also 3.3.8 on 24 GHz for more information on this band).

3.3.3 3.55-3.7 GHz (CBRS)

The most elaborate spectrum sharing scheme is now in operation in the US on the 3.55-3.7 GHz spectrum, formally known as the Citizens Broadband Radio Service. The 3.55-3.65 GHz range has, as its primary user, military radar, primarily aboard Navy ships. The ships are often at sea and primarily fire up the radar near the United States mainland for training and testing purposes. This requires protection, but in most of the country, most of the time, most or all of that spectrum is not being used by the Navy. There are also some satellite downlinks in the 3.625-3.7 GHz range, known as the extended C-band, and their registered earth stations need to be protected as well.

CBRS was created to allow "small cells" and other relatively low power applications to share this band. The 3.65-3.7 GHz segment had been allocated to lightly-licensed fixed applications, primarily used by WISPs and utilities. That segment does not have naval radar. That class of license was shut down, and merged into CBRS. CBRS thus combines fixed and mobile applications.

What is most unique about CBRS is that it has a three-tier licensing structure, where most sharing schemes have two tiers. The three tiers in CBRS are:

- Incumbent. These are pre-CBRS applications, including federal radar and satellites. Some fixed 3.65 GHz users also have incumbent status until their license expires, but most licenses already expired in October, 2020, with a handful expiring between then and January, 2023. All CBRS users must protect incumbents.
- Priority Access License (PAL). These licenses were auctioned off by county, seven per county, each 10 MHz wide. Initially they were to be auctioned by census tract, a sub-county area aimed at a population of about 6000, but the mobile industry petitioned for larger PAL areas, limiting access to utilities and WISPs interested in sub-county areas.
- General Authorised Access (GAA). This is "licensed by rule", which is like unlicensed in most regards but formally a licensing mechanism, as being authorised to transmit by a SAS is counted as being licensed.

Within those three tiers, the scheme of protection is still quite complex. Incumbents are protected by the Spectrum Access System (SAS), so neither GAA nor PAL users can interfere with them. Interference is computed on an *aggregate* basis, so the SAS must predict, using a hybrid propagation formula, the signal level from every CBSD (CBRS Device) in a protected point's "neighbourhood" to the protected point, so that it may, if necessary, reduce their power to keep the sum of the signals under the limit. A neighbourhood can extend over 400 kilometres in some cases, and thus many devices are potentially included. This computation is done by the SAS overnight.

A PAL is protected from excessive interference from GAA within its PAL Protection Area (PPA), which is again based on a propagation prediction, essentially derived from its -96 dBm signal contour. Aggregate interference at any point (computed to a 1 km resolution) within the PPA cannot exceed -80 dBm. A PAL thus does not convey an exclusive right to a frequency, but protection within its PPA. The SAS assigns frequencies to PALs. While a steady-state frequency (i.e., when no incumbent forces a change) is to be pre-assigned to PAL holders by the SAS operators before the beginning of PAL operation in 2021, a PAL retains its protection if its required to move to a different frequency below 3650 MHz. GAA Users on a frequency that a PAL is moved to are thus required to immediately vacate that frequency, to the extent that it interferes with the PPA. The 3650-3700 MHz range remains GAA at all times, so there are no PPAs impacting those frequencies but incumbent protection applies.

There are multiple SAS operators operating in competition with each other. CBSDs communicate with the SAS over the Internet using a standard protocol developed by the Wireless Innovation Forum (WInnForum), a standards body with membership representing manufacturers, network operators, SAS operators, and users. WInnForum standards that impact regulatory compliance are then subject to government review.

Because aggregate interference must be computed among all CBSDs, which must each register with one SAS, the SASs exchange their full registration data overnight. It is thus possible that a device may not be given permission to transmit until this overnight process determines the amount of power that devices, new and existing, are allowed to use, such that the aggregate limits are not exceeded. There is no first-come first-serve privilege; as the band becomes more crowded, power levels for existing devices may have to be reduced. Commercial operation only began around the beginning of 2020.

Government incumbents are protected in near-real time. All CBRS operation must be capable of being shut down by government order, or moved off of a frequency, within five minutes. Radar is detected by a network of Environmental Sensing Capabilities (ESCs). These specialised receivers networks are operated by SAS administrators, and report radar detection to the SAS. This in turn activates the Dynamic Protection Area (DPA) that the ESC is monitoring, an area 10 to 200 km. offshore and typically covering about 100 km of coastline. The location of the ship with active radar is a military secret, so every point in the DPA's 1 km grid is activated, and the SAS follows a previously-computed move list to move CBSDs off of the impacted frequency range.

Figure 5: Dynamic Protection Areas in CBRS and their neighbourhoods that require ESC-coverage for category B (outdoor) operation.

Besides disruption from actual radar, which has precedence, the ESC system has disadvantages. It can falsely detect radar. It also requires the ESC receivers themselves to be protected, so that CBRS may not be used near them, but their location is secret, so CBRS users may have trouble predicting where, along the coastline, operation is thus prohibited. The CBRS user community would prefer an informing incumbent system, but the federal government has not agreed to that yet. There are two ESC networks, one shared by two SAS operators, so only those three SASs can operate within a few hundred km of the coastline, which includes the most densely-populated parts of the country. Additional ESC networks (a third has been approved) worsen the protection problem.

CBSDs are limited in power to +47 dBm/10 MHz EIRP. Every CBSD must register with a SAS and be given a Grant (the right to use a frequency). Authorisation to transmit is then granted via a heartbeat exchange and that authorisation lasts no more than five minutes at a time.

Client devices on CBRS are typically not CBSDs but End User Devices (EUDs), such as handsets and laptop computers, are limited to +23 dBm/10 MHz and are authorised to transmit by connecting to a CBSD base station. They are not considered in the aggregate interference calculations. Higher-powered fixed clients are CPE-CBSDs and must also register with the SAS after connecting to a base station CBSD, and their power and interference levels are counted the same as other CBSDs.

The CBRS band is essentially an experiment in sharing, with many aspects being tested at once, including the SAS, external sensing (ESC), hierarchical licensing, interference aggregation, and fixed/mobile sharing. This complexity slowed down its rollout, which took about four years after the formal Rules (Part 96) were promulgated by the FCC. To some extent its original vision is being compromised by the so-called "race to 5G", wherein mobile operators are calling this 5G spectrum and attempting to bend the rules in their favour as a result. But it has attracted a large number of users and vendors in its short time in service, and a number of refinements and improvements in the industry standards (WInnForum Release 2) are pending.

A number of other details of CBRS were created to increase the trust that incumbents have in the SAS-based system. Communications between the CBSD or its Domain Proxy and the SAS must be encrypted. The protocol itself is based on HTTP over TLS certificate-based encryption. Very strict standards apply to the allowable root Certificate Authority. This ensures the authenticity of both sides of the connection and prevents most attacks.

An additional feature unique to CBRS is its requirement for a Certified Professional Installer (CPI). The CPI need not be, and typically is not, the actual field installer, but is personally responsible for certifying the accuracy of data entered into the SAS. The SAS checks the digital signature of the CPI for validity every time an entry is made. The CPI's signature is a certificate issued by a CPI training program administrator (TPA) approved by WInnForum. If a CPI violates the rules or norms, the certificate can be suspended or revoked by the TPA that issued the certificate.

3.3.4 3.8 – 4.2 GHz band

In the UK, Ofcom has decided to allocate the 3.8 – 4.2 GHz band for spectrum sharing, after a consultation focused on geographical (spatial) sharing in 2016 (Ofcom, 2016). The subsequent decision to allocate this band to spectrum sharing, has triggered interest in both Australia and Canada.

In response to Ofcom's consultation the main issues submitted were:

- VSAT and Satellite operators see problems with the sharing plans: infringement on / interference for Fixed Satellite Services
- Mobile operators (again) responding they want nationwide licenses and continue questioning the use case of local licenses
- Various respondents promoting a 3-tiered spectrum sharing approach (a.o. Fairspectrum, Google)

Ofcom than decided to allocate this band for sharing with geographical local licenses.

Australia has consulted their market on the band 3.7 – 4.2 GHz to reclassify it to a preliminary replanning stage (ACMA, 2020), while Canada ran a consultation in 2020 on the 3650 – 4200 MHz Band and Changes to the Frequency Allocation of the 3500-3650 MHz Band (ISED, 2020).

In its questionnaire introduction, ACMA, the Australian regulator, also mentions Japan as considering these bands, besides the Ofcom decision to open this band for spectrum sharing.

For the Australian consultation a set of responses is made available, but not yet a final decision announced. A large number of responses came from a large group of satellite operators, who in various wordings opposed the replanning proposals and saw a lot of problems appearing.

On the other hand the Wireless ISP association of Australia was strongly in favour of the implementation of a Dynamic Spectrum Licensing Management in the band. Mobile operators pleaded for 100 MHz lots (to be reserved for 5G services).

The Canadian consultation was partially inspired by the fast move of the American FCC in their C-band Auction (which concluded with record revenues of US $80.92 Billion at January 15th, 2021 (Rayal, 2021)). The responses to their consultation haven't yet been published.

Due to the large success in the USA, there is a near certainty that soon 5G NR chipsets (TDD) will be mass produced and made available on the market for at least the frequencies up to 4 GHz.

This strongly influences the chances of allocating and implementing dynamic spectrum sharing in these bands.

Ofcom has now allocated this band for dynamic spectrum sharing, and at this time we see (among others) the CBRS Alliance, recently rechristened into the OnGo Alliance, coming up with proposals to introduce CBRS for this frequency range.

In the Netherlands, and in many other countries, this band is allocated for fixed point-to-point connections as well as for satellite downlink. In the Netherlands, the band is only used for satellite downlink at this time.

3.3.5 5 GHz (U-NII)

The 5 GHz band is, along with 2.4 GHz, one of the most popular bands for unlicensed applications. It is of course widely used for Wi-Fi, as it supports the 80 MHz channels used by 802.11ac. It is also used for outdoor applications, including WISPs, unlicensed point to point microwave, and various public safety and security applications such as cameras. It is divided into several sub-bands, each with their own rules, as it is shared between unlicensed use and other applications, some federal.

The 5.725-5.850 GHz segment was the first to be opened for general unlicensed use in the US, as it was an ISM band. Rules promulgated in the 1990s were quite lax, allowing a one watt conducted power limit and requiring out-of-band emissions to be suppressed by only 20 dB. EIRP could be up to +36 dBm on point to multipoint devices, while no limit applies to antenna gain or EIRP for point to point devices that remain within the conducted limit. Narrowband applications were (and are) allowed; full power need only be spread over 500 kHz.

In 1998, the FCC approved another set of rules, U-NII, which had stricter emission limitations. U-NII-1, from 5.15-5.25 GHz, was initially only authorised for indoor use at low power (+24 dBm EIRP). Part of that spectrum is used as the uplink for Low Earth Orbit satellites, specifically Globalstar, and there was concern that outdoor applications might raise the noise level and impair its performance. The U-NII-2 sub-band from 5.25 to 5.35 GHz was authorised for indoor and outdoor use with a 30 dBm EIRP limit. U-NII limits power spectral density such that full power only applies on a 20 MHz or wider channel. The 5.725-5.85 GHz segment was authorised as U-NII-3, allowing the same power levels as the ISM rules had, but because ISM rules remained in effect for the same frequencies and were less stringent, few devices were actually authorised as U-NII-3.

Several years later, the 5.47-5.725 GHz segment was added to U-NII-2. Both U-NII-2 segments are required to have radar detection and dynamic frequency selection (DFS) for all access points. A frequency must be vacated for at least 30 minutes if the device detects one of several radar patterns, and must listen for at least one minute to a DFS frequency before using it. The 5.60-5.65 GHz segment is particularly sensitive; it is used by many airports for Terminal Doppler Weather Radar (TDWR). Users within 35 km of a TDWR must not operate within 30 MHz of its frequency. Many devices are not approved to operate between 5.58-5.66 GHz because they are not sufficiently sensitive to radar.

However, in 2014, the FCC made several changes. New broadband equipment approvals under ISM rules were stopped, requiring them to conform U-NII-3 (5725-5850 MHz) rules instead. The U-NII-1 (5150-5250 MHz) band was opened to outdoor use with a 1 watt (+30 dBm) conducted, 4 watt (+36 dBm) EIRP limit for point to multipoint Aps, and a 53 dBm EIRP limit for fixed point to point devices. Client devices are allowed +24 dBm conducted, +30 dBm EIRP. Note that fixed client devices are treated as point to point devices in practice; thus outdoor client devices such as WISP and camera radios are allowed +53 dBm EIRP on U-NII-1.

However, the out-of-band emission limit at the 5.15 GHz band edge is limited to -27 dBm/MHz, which proves to be the limiting factor in many devices' allowable power. The lowest standard Wi-Fi channel, 5.17-5.19 GHz, leaves a 20 MHz guard band because inexpensive devices' channel mask is inadequate to approach the band edge. The out-of-band emission rules at 5.85 GHz are much looser, with the level declining to -27 dBm/MHz at 5.925 GHz, 75 MHz out of band.

In 2020, the FCC announced an intention to open up 5.85-5.895 GHz as well to unlicensed use. This 5.85-5.925 GHz range was previously allocated to Intelligent Transportation Services, but saw little use. Vehicles will instead be allowed to use 5.895-5.925 MHz for nascent C-V2X (cellular vehicle to everything) services, while 5.85-5.895 is opened to unlicensed use as U-NII-4. However, the U-NII-4 band is used for government radar in a number of locations, and there will be exclusion zones surrounding them. Final rules for enforcing this are being worked out. It may require GPS in the access point and querying a server to determine if the device is in an exclusion zone, or the Automated Frequency Coordination mechanism being developed for 6 GHz may be used. Some of the radar only operates intermittently and there is also consideration of time-based sharing in some locations.

3.3.6 6 GHz

In 2020, the FCC introduced new rules for sharing the 5.925-7.125 GHz band, known as 6 GHz, with unlicensed users. There are actually four sub-bands, each with their own licensed incumbents.

· 5.925-6.425 GHz (U-NII-5) is currently shared between Fixed Service (FS, meaning point to point microwave) and C-band satellite uplinks. FS licenses are coordinated and must use high performance antennas (minimum gain 33 dB and specified off-boresight rejection minimums). This is the principal band for long-range microwave systems.

· 6.425-6.525 GHz (U-NII-6) is currently used by broadcasters for remote pick-up, such as sports events and news gathering, on a fixed and mobile basis. Cable systems may also use it to relay television signals.

· 6.525-6.875 GHz (U-NII-7) is also primarily used by FS, with some satellite uplinks.

· 6.875-7.125 GHz (U-NII-8) is used by broadcasters for remote pick-up, as well as for television studio to transmitter links. Wireless microphones and portable cameras used by broadcasters also operate on this band, primarily indoors.

In addition, 6.65-6.6752 GHz is protected for radio astronomy purposes.

One form of unlicensed sharing already permitted on this band is ultra-wideband (UWB) operation, used for short-range radar, wall imaging, surveillance, and medical imaging. UWB is allowed over large portions of the spectrum, with very low power spectral density, and UWB interests were among the opponents of further sharing of the 6 GHz band. However, as unlicensed users, they are not entitled to protection.

The FCC’s adopted policy for 6 GHz essentially divides operation into two power categories, Low-Power Indoor (LPI) and Standard Power. LPI devices are, as the name implies, limited to indoor operation, and are allowed to operate across the entire 1.2 GHz range. This is mainly intended for high-speed Wi-Fi, such as Wi-Fi 6E. The LPI power limit for access points is +30 dBm EIRP, but the power spectral density limit of 5 dBm/MHz means that maximum power only applies on a 320 MHz-wide signal. This level is assumed to be low enough that, in conjunction with building entry loss, it will not cause harmful interference to any licensed user.

Standard Power devices may operate indoors or out. Standard Power access points must include geolocation capability, and are allowed up to 36 dBm EIRP, and a power spectral density of 23 dBm/MHz, which permits full power in a 20 MHz channel. Standard Power access points are database-driven. They must connect to an Automated Frequency Coordination (AFC) system at least daily (with a 1-day grace period). The AFC[12] informs the device of what power level it is allowed to use on which portion of the spectrum, between +23 and +36 dBm.

The AFC is central to Standard Power operation. It is required to use a hybrid propagation prediction methodology, similar but not identical to what is used on CBRS, to forecast interference to protected points, which are in most cases the receive points of licensed FS microwave paths. Standard Power devices may only operate on the U-NII-5 and U-NII-7 bands, where all incumbent users are fixed. Broadcast auxiliary stations on U-NII-6 and U-NII-8 may be mobile, which makes AFC-based protection impractical.

Client devices are limited to 6 dB lower than authorised for the corresponding type of access point. Thus an LPI client is limited to -1 dBm/MHz and standard power to -17 dBm/MHz. Fixed outdoor client devices, such as those used by WISPs, may use the same power as Standard Power access points, but will also require geolocation, not a standard feature in clients.

[12] The Automated Frequency Coordination (AFC) service is provided by an AFC provider

Unlike CBRS, 6 GHz sharing is based on individual units' not interfering with incumbents. No Standard Power device is allowed to have a predicted signal strength more than 6 dB below the noise level (I/N of -6 dB) at any protected receiver. Interference is not aggregated. Thus there is no reason for AFCs to exchange data with one another and there is no equivalent of the CBRS SAS to SAS protocol. There may be many AFCs, and while there is a Multi-Stakeholder Group addressing device to AFC communications, there is no requirement that all devices use a standard protocol, although most vendors are likely to converge on one. A manufacturer could, at least in theory, operate an AFC with a proprietary protocol for the use of its own devices. All AFCs do need to retrieve daily updates from the FCC's Universal Licensing System, a rather complex relational database in which all microwave license details are stored.

In keeping with the general technological independence of United States frequency allocations, no particular technology is dictated for use on the 6 GHz band. While Wi-Fi is the obvious target, LTE (or NR) is also possible, or even LTE Licensed Assisted Access, in which LTE downlink carrier aggregation onto an unlicensed band is accompanied by an uplink and one downlink carrier on an exclusively-licensed band. LPI is somewhat more restrictive than Standard Power operation; such devices must employ a contention-based protocol.

An extension of LPI operation for outdoor use, referred to as Very Low Power (VLP) operation, is currently being considered as well. This is proposed to have an EIRP limit of 14 dBm and a power spectral density limit of -8 dBm/MHz, thus assuming a 160 MHz channel for maximum power.

3.3.6.1 Indoor Wi-Fi in the UK

In the UK, Ofcom has made a part of this band (5.925 - 6.425 GHz) available for Wi-Fi, enabling indoor and very low power (VLP) outdoor use. After modelling the potential for interference on existing point-to-point links, Ofcom decided not to require any form of central database access, but simply to rely on sufficiently low power and indoor to outdoor attenuation to avoid interference.

In Europe, the ECC has decided[13] that the same part of the 6 GHz band can be made available for Wi-Fi, as long as existing applications are protected. This can be achieved by limiting the use to low power indoor and very low power outdoor use, as is already happening in the UK, but it can also be achieved through some form of geolocation and AFC database.

3.3.6.2 Offshore microwave links in the Netherlands

In the Netherlands the use of 6 GHz and low 7 GHz microwave links is between shore (The Hague, Den Burg (Texel) and West-Terschelling) and off-shore drilling islands in the North Sea operated by Tampnet A.S. since 2018. They are contracted out by the Telecoms Offshore User Group Holland (TOUGH) a group of off-shore rig owners, who own the North Sea microwave link network.

On land there is a network of long-distance microwave links between the high Radio and TV-transmitter towers using frequencies from 5.9 to 7.1 GHz. Those links are operated by Broadcast Partners and carry digital feeds for FM- and DAB-radio broadcasting from the studio's to the transmitters. Since the late 1990s most long-distance microwave links in the Netherlands used for voice and data traffic, were decommissioned due to abundance of fibre routes. The far majority of microwave links today consists of base station backhaul at frequencies above 10 GHz.

Hence Broadcast Partners and TOUGH (Tampnet) are the two main fixed service spectrum incumbents (primary users) in the 6 GHz band, which are stakeholders for a potential pilot with AFC or an eLSA trial for these frequencies in the Netherlands.

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[13] CEPT/ECC Decision (20)01

3.3.6.3 Car to car communication

Cooperative Intelligent Transport Systems (C-ITS) operate around 5.9 GHz in the license free realm. We have discussed the C-ITS / automotive case in an interview as an example of spectrum sharing between two competing technology approaches. There are currently pilot projects in this realm [see https://www.car-2-car.org/about-c-its/]. However we cannot get away from the impression that a part of the debate / disputes in recent years about sharing the spectrum between two incompatible technologies: 802.11p based devices and LTE V2X for C-ITS is more a classic 'Solomon's judgement' for a classic 'standards race' or 'standards war'.

There are other issues with ITS. For instance "road tolling" works with cheap, unselective receivers in cars and at the tolling gates and therefore ITS-systems have to be switched-off during reading at the toll gates. While this might be done by creating a dynamic spectrum database, car makers aren't fond of that approach. Part of the issue is the rather different life cycle of cars vs (RF-)electronics.

In our view one shouldn't misread a 'standards adoption' case with two competing standards as inducive to a pilot/trial. There's a huge chance that within a few years one of the two standards wins by adoption among the major car manufacturers value chains, who ultimately decide the fate of the 'winner' and 'loser'. There isn't a heterogenous end-user market who determine which standard to choose, but a concentrated car manufacturing industry calling the shots.

Sharing in this case adds complexity to chipsets and will make both technologies more expensive. A decision to split the C-ITS frequency band for each incompatible technology (a hybrid approach) and then letting the market decide might solve the issue from a policy perspective, with far lower long-run device costs. But such a decision has to be have international consensus and should be based on long term argumentation with regard to (in)compatibility of technologies[14].

3.3.7 12 GHz

There are remarkably few mentions of sharing above 7 GHz. A presentation by Dr. Martha Suarez, president of the Dynamic Spectrum Alliance, at the September 2020 WinnForum conference, mentions 12 GHz as an 'opportunity for sharing' as well as 70/80/90 GHz.

We consider these very speculative, as we didn't see these bands mentioned elsewhere.

3.3.8 24 GHz

Unlicensed point-to-point operation is permitted in the US in the range 24.050-24.250 GHz. In many countries this is also used as an ISM band (24 - 24,25 GHz.). The antenna must have at least 33 dB gain (characteristic of a 30 cm dish). The field strength at 3 meters is limited to the far-field impact of a 33 dBm EIRP signal, thus limiting the conducted power to 1 mW. (One Czech manufacturer has however homologated a higher EIRP level in the US by testing with a 120 cm antenna, putting the 3-meter test point in the near field.) This is becoming popular as an alternative to the now-crowded 5 GHz band for short backhaul purposes, generally up to 2 or at most 3 km, especially because it can support gigabit speeds.

The primary allocation of this band in the United States is to federal radiolocation. It is also allocated to Earth-exploration satellites and to civilian radiolocation. The latter application includes some vehicle safety radars (parking sensors. Unlicensed operation thus largely protects other users of the band via the sharp focus required of its antennas and the relatively low allowable power.

[14] In this argumentation potential application of 5G-NR as a future alternative for C-ITS can also be taken into consideration.

3.3.9 37 GHz

The 37 GHz band is used by federal entities at a number of military bases around the United States. The FCC and Department of Defense arrived at a geographic sharing scheme that allowed the band to be authorised for civilian use, primarily on an auctioned basis. Coordination zones were created to protect existing operations. The DoD may request additional access for specified applications at specified sites, and the FCC may put them in contact with the commercial licensee, to coordinate future use. The lower part of the 37 GHz band was not included in the geographic-area auction, and in areas no federal operation requires protection, it may be available for non-exclusive civilian licensing.

Some countries have tried to auction off 26 GHz and/or 28 GHz frequencies. Finland, HongKong, Italy, Taiwand and Thailand didn't see competition. They either settled for the reserve price or engaged in direct assignment, due to lack of demand.

Only the USA has seen some competitive bidding (Horwitz, 2020) for high frequencies 37 GHz, 39 GHz and 47 GHz for 5G use.

The jury is still out on whether there is currently a serious need for sharing in high frequencies (above 7 GHz).

4 Taxonomy and ranking sharing concepts

In the first part of this chapter we introduce a taxonomy for spectrum access management models and confine it to the realm of dynamic sharing concepts. This results in a categorisation of concepts and sharing models we will use to classify the variety of findings from our survey of the scholar literature, regulatory policies and spectrum management websites.

In the second part of this chapter we provide a ranking approach for a set of key properties and features of the concepts based on technological aspects, frequency bands and arrangements. That ranking will be used in this study to assess the various dynamic spectrum sharing concepts on aspects such as spectrum efficiency, feasibility and realistic suitability for pilots and trials. Paragraph 4.2 describes this ranking approach.

4.1 A taxonomy for spectrum access (management) models

Figure 6 provides a taxonomy for spectrum access (management) models found in the scholar literature. It dates back to 2007, when Software Defined Radio / Cognitive Radio, as dynamic spectrum sharing was called at that time, was still in its infancy.

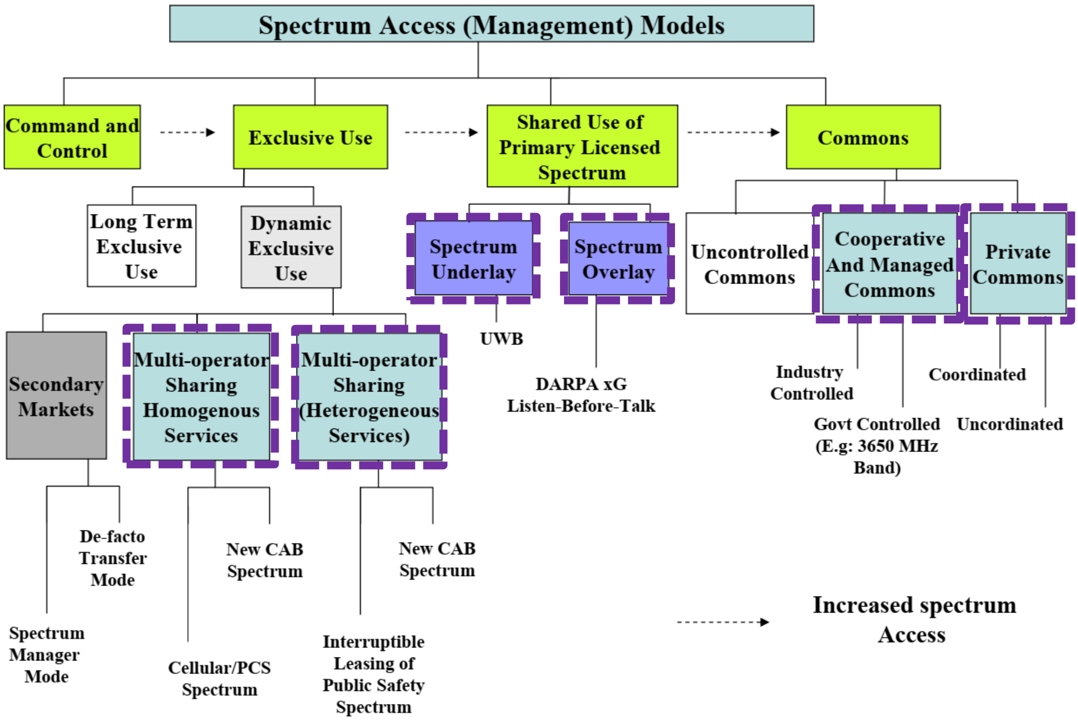

Figure 6: Taxonomy of Spectrum Access Models (Buddhikot, 2007)

In the top taxonomy row, this model splits the realm into command & control exclusive use, shared use of primary licensed spectrum and commons. The Command & Control (C&C) realm historically has been dealt with in the Frequency Allocation of the W(A)RC. It concerns spectrum bands uniquely reserved for military use and public emergency services, prohibitions to use certain frequencies to allow for radio-astronomy measurements and other specific reservations. Also, in a lot of countries frequencies assigned to (national) public broadcasters were in the C&C domain. Most licenses define a right to "Exclusive Use", sometimes with provisions for "Shared Use". When there is no specific licensing regime, the spectrum resource is treated as a "Commons".

Due to growing practices of licensing (commercial) broadcasting frequencies as well as demands to introduce dynamic spectrum sharing in frequency domains originally solely used by the military, several of the former C&C domains have shifted in the last decade (2010-2020) to either Exclusive Use in the category "Interruptible Leasing of Public Safety Spectrum" or Shared Use with Primary and Secondary use and even to what Figure 6 describes as Cooperative and Managed Commons or Coordinated Private Commons.

Comparing Figure 6 with the earlier pyramid of Figure 1 we see both overlap as well as disparities. Figure 1 by WInnForum could be considered as a very coarse type of taxonomy of sharing models, effectively picking and choosing from Figure 6.

It is relevant to consider which parts and elements described in the more generic Figure 6 are left out, or are missed in the WInnForum pyramid.

A key difference is the concept of 'Secondary Markets'. This was a 'big idea' in the 2000s, the idea that licenses could be split up, and traded/transferred/sold or subleased in whole or in part (Spectrum Manager Mode). WInnForum has left the Command & Control spectrum allocation outside its scheme and starts with Exclusive use (Level 0), but introduces at Level 1: Static Spectrum Sharing. It effectively describes this approach as a spatial regional assignment, with a regulator planning the spatial reuse of some of the same frequencies at a considerable distance (avoiding interference by planning and controlling power levels, radiation patterns and antenna heights).

The idea of delegation of a (part of the) band to a Spectrum Manager / Spectrum Broker (not the regulator itself), who subleases frequencies (for shorter or longer periods) hasn't been found at national level. However as a concept it could be introduced at a regional level as a policy option. An example could be in a harbour area with multiple enterprises looking to use a spectrum band in their shipping terminals or industrial plants. A radio agency could decide to delegate the sublicensing for that area in its entirety to the Port Authorities, who then would assign and monitor the actual use of frequencies in the port.

When such a delegated authority would just take over the role of a Radio Agency at a regional scope, and then engage in subregional assignment, it still remains at the 'Static Spectrum Sharing' level WInnForum describes as Level 1.

In Figure 6 the actual realms of dynamic spectrum (management) and sharing are indicated with purple dotted boxes. Two "Multi-operator sharing" realms are shown as New CAB (Coordinated Access Band) Spectrum.

The New CAB Spectrum for multi-operator sharing of homogenous services is today best known as "RAN sharing". An often discussed concept where a part of the mobile spectrum in a band would be shared between multiple mobile operators on a single physical infrastructure. One of the operators would install a base station and the spectrum it uses would be shared by multiple operators.

What becomes clear is that the spectrum underlay (UWB, Ultra Wide Band) and spectrum overlay (a reference to DARPA's first plans to develop listen-before-talk technologies) models described, are focused on **technologies** used for spectrum sharing, while the other elements of the taxonomy are more focused on **policy arrangements**.

This apples and oranges aspect in the details reduces the usability of Buddhikot's taxonomy somewhat, as the individual elements in the taxonomy are either policies / policy arrangements or technologies. It does however signal upfront that there is a (partial) substitution between policies and technologies at play. Even with this disadvantage, Buddhikot's taxonomy is a useful model which is still used extensively.

4.2 A ranking for concepts and models

To answer the questions the suitability of spectrum sharing concepts for pilots and/or proof-of-concepts, it is necessary to provide a ranking that deals with a number of dimensions.

In discussions with the Radiocommunication we further defined what is meant by 'the suitability of spectrum sharing concepts for pilots and/or proof-of-concepts'. In particular, two aspects are important:

1. A relevant pilot or proof of concept should include at least some technologies that are new, or at least new in the context in which they are used. At the same time, it should not require technology which is still in a research stage.
2. A pilot or proof of concept should also address an existing need, or at least demonstrate that an existing need can be addressed using a given combination of technology and policy.

The weighing of rankings to recommend on feasibility will not be done in a rigid cardinal way (attaching weights to each criterium).

We will present this ranking as a concepts vs ranking categories matrix and score each concept against each criterium, where comments and highlights will be used to explain the weighing were necessary.

Criteria by category:

1) Technological concept

a) **Objectives of sharing**
- Is the concept designed for (dynamic) sharing to solve demand questions in 'busy areas' [capacity issues] or to enable reuse of (far-propagating) frequencies with favourable properties in underserved areas [coverage]?
- Does it address temporary dynamic sharing [short timespans]?

b) **Maturity stage**
- What is the technological development stage (from infancy to maturity/aging)?
- Were pilots already conducted elsewhere?
- What is the state of standardisation?

c) **Supply considerations**
- Are devices/chipsets available, or soon to be expected?
- When needed, is a vendor of shared access services systems developing?
- If it concerns a niche market: can the concept piggyback on another technology?

d) **Complexity**
- How complex are the features of the sharing concept?

i) Does it include sensing?
ii) Does it need rules based decision algorithms or elaborate AI / Machine Learning
iii) Does it include (priority users) signalling?
iv) Is there an authentication / trust mechanism (to) develop?
v) Does it reduce frequency assignment burdens / short period assignments?
vi) Is it designed for homogenic or heterogenic sharing?

2) Frequency bands considerations

a) Are there existing licenses / uses in the proposed frequency band?
b) Are these nationwide licenses or spatial constrained licenses?
c) Is it a known empty / underutilised band in the Netherlands (and preferably also usable elsewhere, particularly in other European countries)?
d) How is spectrum congestion measured in the prospected band (today)?

3) **Involved testers and user groups in sharing**
    a) Is the dynamic sharing concept designed to solve demand side economic issues?
        i) Adoption hurdles, usage hurdles on the demand side
        ii) Extension of a technology to new user groups or market segments
    b) Is there a pilot/trial interested (prospective) user group or user segment?
        i) Have they been identified or expressed interest?
        ii) Are the (prospective) users knowledgeable?
        iii) Do users already have congestion measurement / sensing systems?
    c) Can a trusted group of trial participants be organised?

In the paragraphs below we elaborate the rankings and related criteria. The rankings on each aspect are primarily ordinal of nature, but in a few aspects it will not be a straightforward case of 'higher on an aspect is better'.

4.2.1 Ranking criteria for technological concepts

4.2.1.1 Objectives of sharing

Dynamic sharing is a rather broad concept with different objectives. It does however tend to address two main issues of exclusive licenses: one spatial and one temporal.

1. Spatial: not every current license regime (nation-wide, large area) is spatially efficient (lots of empty spaces)
2. Temporal: (exclusive) licensing requires time and cannot easily address short term, short period and ad hoc frequency demands.

4.2.1.2 Maturity Stage

Maturity stage determines to an extent what kind of trial / test is feasible and whether the tests and experiments are more 'bleeding edge' than leading edge, geared toward technological experimentation or more oriented toward adoption / user environment testing.

Supply maturity can be based on already performed trials, needed adaptations to different circumstances, and the state of standardisation.

A very mature technology, not used in the Netherlands, but tested and widely operational in other countries is less interesting from a technological experimentation viewpoint but still may have relevant user environment testing questions.

Mature concepts and technologies that have failed implementation or met limited success and adoption in other markets will be earmarked, as deciding on them needs more justification (in particular in user group / use case realms).

Standardisation state is relevant. Trials and tests could be needed to address technical standardisation questions or sometimes a 'show of concepts': plugfests (interoperability tests/demonstrators) and hackatons tend to address earlier stages of development and standards issues.

4.2.1.3 Supply considerations

This is an assessment of the readiness of the supply side. The availability of devices and ecosystems is always relevant, ranging from ready to use hardware and mature software to devices at the breadboard level. The latter is more suitable for proof-of-concepts and experimentation.

When a technological concept demands not only device innovation but a set of special developments for (centralised) systems, brokers, authentication platforms, sensor data collection etc., an appropriate question is to ask for their availability and the state of development willingness/interest of suppliers in that realm to engage in trials.

For niche markets it is relevant to assess whether a concept can piggyback on existing technology. As an plain example: electric cars are several centuries old as a technological concept and already drove around in the late 1800s. Firms like Nokia, Samsung, Apple, Sony-Ericsson and the IT industry for laptops / tablet have effectively funded battery innovation and R&D since the 1980s. Electric car start-ups or car manufacturers that sprang up in the 2000s piggybacked on the battery improvements, reaping the benefits without needing to fund battery innovation.

A spectrum sharing technology destined for a spectrum niche market with limited scale is expected in several highly professional, but limited scale (in absolute numbers) user groups.

For instance PMSE, and some Emergency, Public Safety and Military domains, operate on a 'limited scale' and probably need to piggyback on technological trajectories for feasibility.

4.2.1.4 Complexity

Another consideration is the complexity of the overall scheme in terms of technology required, but also in terms of the number of stakeholders involved and the organisational complexity.

A concept that attempts to introduce 'jump innovations' or 'breakthrough innovations' in many realms all at once, tends to be a far higher risk than a concept which only requires changes in one realm.

4.2.2 Ranking criteria for frequency bands

We evaluated the issues related to frequency bands, and in particular whether other users and applications exist and whether sharing addresses existing problems (such as congestion in these bands), or other issues related to frequency bands (accessibility for certain uses, not easily solved by other means).

Not all technologies or concepts are usable or proposed for all frequency bands, although some sharing concepts can be used or extended in multiple frequency bands.

Hence we do expect to find some links between a concept, model or method and some (congested or underutilised) frequency bands it is proposed for.

4.2.3 Ranking criteria for trial testers/user groups

The involvement of user groups and in particular trial testers (users that are willing and flexible enough to participate in pilots is particularly relevant for regulators and radio agencies. While a concept being tested could have a potential to alleviate the burden of the regulator or radio agency itself (as a dynamic sharing concept / approach reduces planning burdens), the main issue is the prospective user groups for a concept or method and whether they would be interested to participate in a trial.

5 Stakeholder perspectives

5.1 From a fixed mindset to a growth mindset

When reviewing the material from a set of conferences on Dynamic Spectrum Sharing, as well as the policy websites of several regulators, it becomes clear that Dynamic Spectrum Sharing requires a change of mindset both in the regulatory approach as well as in the way market participants operate.

The table below provides a list of 'key differences' given in a talk at the Dynamic Spectrum Alliance Summit of November 2020.

Table 2: List of 'key differences' of a changing mindset toward spectrum use

A Fixed Mindset	A Growth Mindset
Spectrum Scarcity	Spectrum Abundance
Static, Exclusive Allocation	Dynamic, Shared Access
Avoid Interference	Mitigate Interference
Worst-case driven rules	Real-time data driven rules
Spectrum as property	Spectrum as service
Get it and guard it	Use it or share it
Regulatory opacity, distrust	Regulatory transparency, trust
Regulatory certainty	Regulatory agility
Reg Intensity	Tech Intensity
Political Spectrum	Computational Spectrum
Spectrum Competition	Spectrum Collaboration

(Yan, 2020)

The toughest aspect from this list, in our view, is the shift from Spectrum Competition (based on exclusive licenses) toward Spectrum Collaboration.

In general a cultural shift towards mutual trust between the collaborators is needed in order to enable spectrum sharing. In particular when a heterogenous set of users is involved, this requires time.

When reviewing the policy consultations / proposed rule making websites of regulators / radio agencies on dynamic spectrum sharing proposals, it is clear that most respondents write from the Fixed Mindset and not so much from the Growth Mindset listed above. In our interviews we notice both mindsets: many organisations that are represented by interviewed parties still work from the Fixed Mindset, but most interviewed parties realise that the shift towards the Growth Mindset is inevitable and are trying to help move their organisations in that direction.

5.2 Opportunities for spectrum sharing in the Netherlands

To assess market-readiness for (dynamic) spectrum sharing, and get a view on the practical implications that can be expected, professionals from several different sectors that might benefit from sharing were interviewed. This section reviews their views on trials or pilots. A more elaborate review of the interviews can be found in the annex.

5.2.1 Interviews: organisational and regulation aspects are more important than technology

The field interviews provide a different, more practical take on the matter. The difference between the technical and practical reality was noted by the interviewees, stating that while there are opportunities for almost every industry, spectrum sharing poses a big challenge, especially on 'softer' sides like policies and standardisation. At the moment, most parties see contradicting goals, as the spectrum needs to be harmonised and shared. Interviewees noted that most involved parties see the opportunities for a shared spectrum, but are hesitant to share their own spectrum. This contradiction diminishes their willingness for a trial or pilot.

The interviewees all believed in the technical possibilities for pilots, but voiced concern about the regulatory aspects. There was also concern about the economic aspects, as some noted that without a business case, they would not be inclined to take action. Other problems occur in the domain of standardisation. The automotive vehicle industry, for example, is still working out standardisation as different ways to communicate compete to become the standard. For some companies, sharing spectrum will at this point be disadvantageous with regard to their competitiveness.

5.2.2 Festivals, harbours and airports may be feasible environments for pilots , with limitations

Sectors that were more enthusiastic about possible pilots are, for example, the events sector. This sector already has experience with experiments in the frequency domain, like wireless wristbands that are given out to festival attendees. Events also provide a situation with a lot of different frequencies 'in the air' and have a lot of issues with interference, thus providing a good testing environment for the technology. Upon that, they are pre-planned. This makes events alike festivals a good opportunity for a trial due to the technical lay-out. However, they are a less obvious choice on economic grounds. For performers on a festival, there is no benefit in participating in a spectrum-sharing trial. Upon that, artists insist on the importance of reliable equipment when performing. If reliability cannot be assured, artists will not commit to a trial. Latency (possibly due to a database-based sharing mechanisms) can also be an obstacle.

Practical experience in the industry shows that large events require on-site spectrum measurement sweeps as regular unexpected, undeclared / notified sources of interference are discovered. It is, together with EMC-problems from electrical devices, why these secondary users of the TV White Spaces still use in-person frequency coordinators.

Sectors that do benefit from spectrum sharing due to their usable spectrum becoming more and more crowded, like airports, are reluctant to commit to a full pilot. They have mission-critical systems they cannot risk to become unavailable. However a pilot in such an area could focus on spectrum sharing in spectrum that is not used for mission-critical systems.

Other sectors that see the benefits, but do not want to take certain risks are the emergency services. There might be opportunities for trials in areas with less security issues, on a local scale, possibly only in a certain part of the spectrum. An example that conforms to these requirements might be found in a harbour, for example for communication options for automated guided vehicles (AGV) (this is also an option at an airport). Other noted options are a shared system on the frequencies of construction companies, while at work at an airport.

Emergency services may also be interested to use various types of shared spectrum for non-essential functions at disaster sites, where the spectrum available to them (mainly the C2000 TETRA network) is completely filled with essential traffic.

5.2.3 Pilots are feasible, but difficult to find a non-critical use case

Concluding, all of the interviewed parties were hesitant to commit to a pilot. The noted concerns mostly had to do with the reliability of the services. A pilot that can be held on only parts of the spectrum might be an option. If a pilot like that is undesirable, they aim could be to find or host an event with less mission-critical communication, or find a location with less mission-critical communication. The latter however will likely not provide a very crowded spectrum and might thus not meet the goals of a full trial.

5.2.4 Building trust in the system, operators vs other users dynamic

From the interview on the efforts to get CBRS in the USA off the ground, we learned that in particular organising and aligning the user side in the (cooperative) arrangements was by far the majority of the effort. The actual sharing arrangements then followed more easily.

An underestimated aspect in our view is the importance of the authentication mechanisms. In CBRS certificates are used, in a similar way as most websites today are certified for "http secure (https)" to authenticate (and encrypt traffic). That implies a Certificate Authority (a Trusted Third Party service) which must also be included in a pilot with end users.

Also, there is potential countervailing effort to be expected from those who are strongly invested in the "spectrum as property" paradigm (as mentioned in paragraph 5.1). Spectrum as service requires a shift in economic policy attitude.

6 Conclusions and recommendations

In this chapter we combine the findings from the previous chapters, in order to answer the research questions as defined in section 1.2.

6.1 General conclusions

6.1.1 Spectrum sharing is becoming increasingly important

There are two major reasons why spectrum sharing among different parties and in particular dynamic spectrum sharing are becoming increasingly important:

- The first reason is that there is a constant and practically unlimited growth of data communication needs. This holds for the classical MNOs, but on-top a whole new category of so-called verticals is appearing, e.g., to satisfy the needs of Industry 4.0. Many of them run applications that demand QoS guarantees or other features which the MNOs cannot or will not satisfy. Many of these applications are mission critical or business critical. It is likely that a niche set of applications will remain, with valid arguments for separate networks, and therefore a need for specific radio spectrum or (dynamically) shared spectrum with other users.

- The second reason is that there is a growing number of unplanned or unpredictable situations that require communication and are potentially disrupting the communication infrastructure, e.g., in emergency situations or temporary events that require a lot of data communication capacity (e.g., sports events, outdoor concerts). The time requirements may be vastly different for different cases, e.g., disaster management may demand immediate creation of capacity, while sports events can be planned for.

6.1.2 The search for shareable radio spectrum and sharing methods intensifies

The search for extra spectrum to satisfy the growing demand can, to a certain extent, be satisfied by the hitherto unused huge amounts of spectrum available at frequencies above 6 GHz (from mmWave to the near-THz range). However, this opportunity can only be used for short distance transmissions and hence requires a dense and costly infrastructure. The latter problem can be alleviated by sharing infrastructure among parties (see Section 2.3.7 on radio virtualisation and infrastructure sharing) and by exploiting the space dimension for sharing (see Section 2.3.4 on spatial spectrum sharing).

However, the sub 6 GHz frequencies are the most critical, since they are needed for coverage, and this is where the biggest crunch exists.

A number of methods have been proposed with the following motivations:

- To achieve a more efficient utilisation of spectrum, in the sense that the network data throughput in a shared scenario, provided the demand is there, is maximised.
- To allow new and different players than allowed by the static exclusive allocation, e.g., verticals, Industry 4.0, PMSE, etc.
- To increase capacity through carrier aggregation for traditional MNOs., by combining licensed and unlicensed spectrum.
- To create the possibility for guaranteeing QoS for specific users both for the original (primary) users, and for the additional (secondary) users.

6.1.3 Considerations with regard to spectrum sharing methods

Much more unused spectrum can be found, and delays to acquire spectrum can be reduced drastically, by taking a "microscopic" look at spectrum usage, e.g., at the transmission burst level, the level at which MAC protocols operate. To exploit this huge potential, radically new approaches to spectrum sharing are proposed, and much wider spectrum bands are considered than is presently the case. The leading example is the DARPA Spectrum Collaboration Challenge (SC2) (see Annex F). Key to real-time dynamics are technologies that can perform, enable or support such dynamics such as cognitive radio, software defined radio (SDR), reconfigurable antennas, complex spectrum sensing, AI machine learning techniques, collaboration between the sharing parties and better interference mitigating techniques, including full-duplex radio. Some of these techniques are discussed in Annex G.

Distributed ledger ("blockchain") technology may play a role in future spectrum sharing as a mechanism to maintain distributed, trusted information about available transmission opportunities.

The most common use of radio frequencies with the shortest product life cycles can be found at the mobile 3GPP based networks. This also means that many technological innovations regarding efficient use of radio spectrum have at some point been proposed, tested or (optionally) standardised in 3GPP. At this moment almost all solutions to dynamic spectrum sharing fit in some way or another in the 3GPP context, i.e., they appear on the 3GPP Release roadmap and/or were developed in research projects with a strong participation of the 3GPP stakeholders (see Annex for a survey of projects). 3GPP based products provide a useful toolbox of functionality for organisations that are able and allowed to configure and program these toolboxes. Even for sharing mechanisms defined outside of the 3GPP context, the sharing protocols may be different but the actual radio interface can follow 3GPP standards.

6.2 Research question 1: concepts for pilots

1) ***Which concepts of dynamic spectrum sharing are promising for concrete application(s) (potential pilots, trials and/or 'proof of concepts')? Please, be specific and concrete, and provide a substantiated 'ranking' (f.i. in terms of spectrum efficiency, feasibility / realistic for pilots).***

The paragraphs below provide the answers to the sub questions. The overall concepts for pilots or proof-of-concepts are discussed as part of question 2 (frequency bands), as not all concepts are useful in every frequency band.

6.2.1 User groups and use cases

a. ***For which type(s) of users (or user-groups)? It concerns at least of two users/groups, who are assigned different 'rights of use' (like primary vs secondary or licensed vs license free. It is not needed to elaborate a scenario with only license free applications).***

In order to identify user groups with an existing need, it would make sense to focus on spectrum "hot spot" areas where a local solution can provide advantages. In the Netherlands, permanent hot spot areas are Schiphol Airport and the Rotterdam container terminals. There are also temporary hot spots surrounding large events (Sail, music festivals, etc), as well as at major disaster sites (fires, explosions, etc).

User groups in those areas who could benefit from secondary use are:

- PMSE users (wireless microphones, video etc), particularly at events;
- Logistics users (self-driving or remote-controlled container transport vehicles), in the permanent hot spots Schiphol and the Rotterdam container terminals;
- Emergency services, at large events (such as Sail Amsterdam) and at disaster sites.

Note that all of these user groups have one thing in common: they require a certain amount of guaranteed bandwidth for their operation. So any opportunistic spectrum access mechanism would be an addition, but not a replacement, to their existing communication channels (which in many cases are based on exclusive rights).

Some IoT applications have less stringent minimum requirements (for instance, sensors which only need to provide data once per day), so they could use shared spectrum. However, there is little evidence that this would actually address an existing need, as there are already various options to address this segment (public LTE, private LTE, LORAWAN, etc).

Which primary users are involved will depend on the frequency bands chosen (refer to section 6.3). Generically, any primary user who does not use the full potential of its assigned frequency bands could provide space for spectrum sharing. This includes:

- Broadcast users, as broadcast applications tend to need large separation (as illustrated in paragraph 3.3.1);
- Radar users, due to the low duty cycle, particularly for rotating radars;
- Defense and emergency services, as they do not need all their spectrum all of the time, but do need guarantees that it will be available when needed;
- Mobile operators, particularly in high frequency bands, in areas where the low bands provide sufficient coverage and capacity.

6.2.2 Assessment of feasibility and identifying promising technologies

b. *Which (existing) radio systems/applications are appropriate for dynamic spectrum sharing?*

c. *Which basic techniques and methods (for instance AI (Artificial Intelligence), sensing, DSS within cellular networks, database) lend themselves for dynamic sharing and why?*

In order to assess which spectrum sharing technologies are the most promising for trials or pilots, a matrix was devised and the concepts were scored along that matrix. Below, the results of this process are discussed.

6.2.2.1 Ranking criteria

When we consider the technologies discussed, the primary assessment is on the development stage (maturity level, from drawing board via prototypes to operational). A pilot or proof-of-concept based on mature technology and existing sharing mechanisms may not provide new insights, whereas a technology which is still in the research phase may not be mature enough for a pilot.

Also important are the supply considerations: are equipment and software available. And finally, the complexity of the overall sharing arrangement can make a concept less attractive.

The ranking criteria are explained in more detail in section 4.2.

6.2.2.2 Ranking the technologies

Based on the reviews, literature, desk research and input from the interviews we established a high level ranking on the aspects mentioned above of the main technologies used in spectrum sharing, as shown in

Table 3. A more elaborate technology version of this same ranking table can be found in Annex A.

Objectives

The technologies shown in the ranking table are all designed for (dynamic) sharing to solve demand questions in 'busy areas' or to enable reuse of frequencies with favourable properties in underserved areas (category 1.a of the criteria in paragraph 4.2, see also paragraph 4.2.1.1).

Maturity stage

Category 1.b of paragraph 4.2 was the maturity stage, described further in paragraph 4.2.1.2. If we consider the technologies described in chapter 2 and their implementation in paragraph 3.3 the most mature technologies are:

- databases used for spectrum sharing;
- sensing technologies, in particular energy detection, time/frequency/power sensing, and detecting specific signal characteristics ;
- synchronisation between devices ;
- virtualisation and infrastructure sharing.

Beaconing and blockchain technology for spectrum sharing are both in the pilot stage.

Space based detection, localised spatial sharing, full duplex radio, and the use of Artificial Intelligence / Machine learning for spectrum sharing purposes are all at a research stage.

Supply considerations

This refers to category 1.c of paragraph 4.2 (see also paragraph 4.2.1.3). For geolocation and reservation, companies are already offering database services. For most sensing technologies except space-based detection, chipsets or firmware on devices are available. However, the chipsets available are often specific to the frequency bands in use for current sharing arrangements, making it more complex to implement similar arrangements in different bands.

Although Software Defined Radio (SDR) and reconfigurable antenna’s enable more flexibility, these technologies have not yet achieved the point where a simple end-user device can be dynamically changed to cope with different sharing mechanisms. Transmission technologies specific to spectrum sharing are not yet widely available in chipsets or devices, while spatial sharing and synchronisation are possible using other existing technologies. This is also the case for AI/Machine learning.

Complexity

Complexity refers to category 1.d of paragraph 4.2.1 (see also paragraph 4.2.1.4). The least complex technology is the use of a database for reservation of certain channels, in certain places, at a certain timeslot. Also sensing by energy detection is a relatively simple technology, as is (depending on the implementation) synchronisation of transmissions, as long as the devices have access to a reliable time base.

6.2.2.3 Feasible technologies for pilots

Table 3 summarises the results from the synthesis that is provided in the paragraphs above. Note that the table only describes the new or additional technologies that can be used for (more) dynamic spectrum sharing. Decision making, for instance, can be improved through AI or machine learning.

Table 3: Technology ranking (compacted)

		maturity stage			supply considerations			Complexity
		development stage?	pilots elsewhere?	standards efforts?	devices/ chipsets	shared services	piggyback techs	
Geolocation and reservation	Database	deployed	yes	yes	n.a.	yes	yes	low
	Beaconing	pilots	yes (USA)	yes	n.a.	yes	?	medium
	Blockchain	pilot (ANFR)	yes (ANFR)	?	n.a.	yes	yes	medium
Sensing	energy detection	mature	yes	yes	yes	n.a.	partly	low
	Time, frequency & power sensing	mature (radar)	yes	yes	yes	n.a.	partly	medium
	Signal characteristics	mature	yes	yes	yes	yes (CBRS?)	partly	high
	Space-based detection	research topic	yes	no	no	no	partly	high
Transmission	Spatial sharing	research topic	no	no	no	no	yes (MIMO)	very high
	Full-Duplex radio	research topic	no	no	no	n.a.	no	high
	Synchronisation	mature (4G/5G)	no	yes	yes	yes	yes (4G/5G)	low
Decision making	AI/Machine learning	research topic	no	no	no	no	yes	high
Resource sharing	Virtualisation and infra sharing	mature	?	yes	n.a.			medium

From the matrix above, it is clear that a central database is not, by itself, an innovative approach: it is already in use in many different environments. The same applies to energy detection, which is the basis for the Listen Before Talk mechanism implemented in many radio standards. Other forms of sensing, which analyse the received signals based on various characteristics, are mature in some specific combinations but provide scope for further innovation in other settings.

Therefore, a technically relevant pilot or proof of concept would preferably use some form of complex sensing (for instance using pattern recognition) in combination with an existing reservation mechanism such as a central database. Such an approach would require some software development, using existing hardware.

Note that it is also possible, depending on the objectives, to base a pilot entirely on mature technology. While not technically innovative, such a pilot could still explore the legal, organisational and commercial aspects of sharing. For such a pilot, a central database mechanism would be sufficient, combined with a set of rules for the use of spectrum along the lines of the US CBRS system (but revised for a two-tier hierarchy, as there is no clear-cut case for a three-tier model in the Netherlands).

6.3 Research question 2: frequency bands

2) In which frequency band(s) could the concepts you identified be tested and applied and why?

Criteria for frequency bands were mentioned in 4.2.2. We have checked the frequency bands used in existing sharing arrangements (section 3.3) against these criteria; however we have also found some bands which are not used in existing sharing arrangements which also meet these criteria. As it was not feasible to analyse every existing allocation, we made a selection based on our expert opinion as well as on the interview results.

We found that the most relevant bands to test the identified concepts are the DVB-T2 band, the 3.8-4.2 GHz band, the 6 GHz band, and possibly some existing radar bands. There may also be an opportunity in the future mobile bands above 26 GHz.

6.3.1.1 3.8-4.2 GHz band

The entire 3.8 – 4.2 GHz band is currently mainly in use for downlink reception of geostationary satellite communications, for which a limited set of ground stations are situated in the country. In addition, there is a number of UWB applications. This provides opportunities for shared access, taking into account the level of protection that is required for these satcom links.

A pilot or proof-of-concept with this band could use the US CBRS approach to dynamic sharing (again, modified for two tiers), while allowing for 5G NR as the underlying technology. Chipsets and software for 5G NR in this band are expected to become available soon.

The combination of a CBRS-like approach and 5G NR as the underlying technology can be a useful addition to existing communication channels, in particular for emergency services (for instance, for ad-hoc video networks). Therefore this type of pilot should involve the emergency services, or possibly other user groups with similar needs.

6.3.1.2 Existing DVB bands (TV White Space)

The European DVB-T2 band (470-698 MHz) can be used for IoT or PMSE, using a ”TVWS” approach (in addition to the current low-power PMSE general authorisation for that band).

PMSE users can already use these white spaces in the Netherlands, but with severe limitations on transmitted power. Also, they currently have to coordinate among themselves when operating in close proximity, as the Radiocommunications Agency only provides information about primary use in this band, not about other PMSE users.

A more dynamic sharing approach would require a database approach to protect primary use (but this database would be fairly static), as well as an approach to coordinate secondary use devices with each other. The latter could use a much more dynamic reservation database (reservation by day, hour or minute), a sensing approach, or a combination of those two. In order to add value compared to current arrangements, devices should be able access the database and place reservations directly and without human intervention.

Note that the Agency already has a reservation database for Licensed Shared Access in the 2.3 GHz band (also for PMSE users), but that this database is only accessible through human interaction. The pilot would therefore take this a step further towards a truly dynamic approach.

6.3.1.3 6 GHz

The European Commission is expected to confirm the ECC Decision on the 6 GHz band in the near future. While most users will probably use low power indoor devices, which do not require any centralised frequency coordination, there is an opportunity here to allow larger powers and outdoor devices, while protecting existing applications, through a combination of geolocation, sensing, and central database. Potential use cases for this band include the logistics sector (both for permanent and for temporary networks) and the emergency services (for ad-hoc networks at disaster sites, complementing existing critical networks in order to allow for video and other bandwidth intensive applications).

6.3.1.4 Existing radar bands

A large number of frequency bands are allocated for radar systems. Many of these bands are already shared with other applications. In Europe[15] frequency bands used for radar range between 1215 MHz and 248 GHz. However, some of these bands are only lightly used.

Bands currently in use for radar applications can be shared with secondary users, using a combination of database (location, power, frequency and duty cycle of the radar) and sensing (detecting radar pulse timing and sweep timing). This would allow spectrum use, even in the proximity of radar equipment, during the time that the radar is "looking" in a different direction.

The radar X-band (8-12 GHz) is the most likely candidate, as it is current use is limited to a number of locations near waterways ports and airports lightly used. However, this would require hardware which is not currently commercially available. Therefore, this band would be suitable for a technical proof-of-concept, with prototype equipment, but not (yet) for a user pilot which would need off-the-shelf end-user equipment.

6.3.1.5 26 GHz band

The 26 GHz band is currently used for point to point connections and potentially some radar applications. 26 GHz (and also 28 GHz) are proposed as new 5G bands by organisations such as the GSMA. These bands are likely candidates for pilots and trials involving spectrum sharing methods, once they are allocated to land mobile use, as it is likely that operators will use these bands for localised (hot spot) capacity but not for wide area coverage.

Spectrum sharing in these bands would require arrangements to be made in the licenses for primary (land-mobile) use.

6.4 Research question 3: arrangements, rules and boundary conditions

3) *Which arrangements, rules, boundary conditions are needed for this?*

6.4.1 Technical protocol

a. *Technical protocol level: which arrangements, rules and/or standardisation can be applied or is needed for communication between radio-systems or with a central system (if needed)?*

A number of existing protocols for spectrum sharing has been described elsewhere in this report. For the pilots and proof-of-concept cases discussed in the previous paragraphs, a combination of existing protocols should be sufficient. Part of the objective of the pilots will be to establish whether these protocols are suitable for the use cases being tested.

In some cases the protocols for spectrum sharing are intrinsically linked to the standards for communication. In other cases, and in particular for database access and beacon networks, there are existing protocols which may be copied (such as the CBRS approach mentioned in some of the previous paragraphs) while the underlying radio communication is based on a different protocol suite (such as Wi-fi or 5G NR).

[15] https://docdb.cept.org/download/2051

If the arrangement involves multiple central databases, as is the case in the US CBRS arrangement, it is even possible for different protocols to be supported, so that, for instance, a radio manufacturer may build a database and lock its radio systems into it.[16]

Some sharing regimes deal with aggregate levels of interference, and with multiple database operators, such that the aggregate must be computed after all database operators share their registration data. That would require a synchronisation protocol between databases.

However, for a pilot a more simple approach with only a single database would also be possible.

6.4.2 User level

> ***b. At the user level: which (standardised) arrangements and rules can be applied or are needed with or between end users?***

Agreements are needed in the realm of 'industry organisation'. Databases like COIN (number portability) and systems like the Domain Name System ccTLDs were not built in a day, but required extensive collaborative effort and guided discussion. Similar effort will be needed to establish communication and trust between the (primary and secondary) users in any sharing scheme.

6.4.3 Radio technical level

> ***c. At radio technical level: what has to be defined in the area of transmit and receive characteristics (a.o. power, duty cycle, transmitter and receiver characteristics)?***

Sharing regimes such as Spectrum Access Services and Automated Frequency Coordination require knowledge of radio characteristics sufficient enough to determine relevant interference options. Apart from geographic location, elevation (above ground level), a number of transmit and receive characteristics may be useful.

In ETSI EN 300 220 a set of potential characteristics for short range devices are already described, and for spectrum sharing in general these characteristics are also usable (and are used in practice) for other ranges:

- Power (a maximum effective radiated power of a device or e.r.p.),
- Duty cycle (the percentage of time that a device is allowed to send, a maximum duration of a single transmission, a minimum duration of time between transmissions, specific time slots that may be used or combinations thereof). In case of a primary user this only works if also this user has a kind of (de facto) duty cycle, for example radars (which often have two duty cycles, a fast pulse repetition rate and a much slower sweep rate).
- Listen Before Talk (LBT) which is usable for short bursts of transmissions where a device first listens on a channel and sends if there appears no other user sending at that moment,
- Adaptive Frequency Agility (AFA) where a device monitors a number of channels periodically and chooses an unused channel to send.

Transmitters and receivers need to be able to support these characteristics avoiding interference due to harmonics on other frequencies, where possible and applicable also using antenna characteristics and position (antenna gain, radiation pattern, antenna azimuth heading and downtilt) to optimise sending and receiving.

For more complex spectrum sharing methods such as frequency hopping, wideband communication or MIMO variants similar thresholds need to be investigated and applied for these methods to be successful

[16] PMSE manufacturers Sennheiser and Shure already maintain their own databases with local information about frequencies. See https://en-us.sennheiser.com/sifa and https://www.shure.com/en-US/support/tools/frequency-finder

in technology agnostic environments. In other methods it is feasible that also identity or version of the equipment used, identity of the user, identity of the organisation who made the database entry are stored.

6.5 Recommendations

Dynamic Spectrum Sharing clearly has the potential to help resolve existing spectrum shortages, but users groups are hesitant to experiment, due to the technical and regulatory complexity. Therefore the Radiocommunications Agency should take the initiative to develop a set of pilots, in order to create momentum.

For each pilot, the Agency should identify the user groups, frequency bands and mechanisms to be used, based on the results listed in this report. The Agency should establish clear objectives for each pilot, and discuss these with the user groups involved. Those objectives may include technological innovation, but also exploring the legal, organisational and commercial aspects of sharing.

While the pilots can be based on experimental licenses and on temporary agreements with primary users, further implementation may require additional regulation. Particularly for new spectrum licenses, the Agency should examine possibilities to include sharing conditions in the license, in order to ease the way for Dynamic Spectrum Sharing in the future.

Stratix

Annex A Ranking matrix

Table 4: Spectrum sharing technologies ranking matrix

		maturity stage			supply considerations			Complexity	User hierarchy			Radio technologies		
		development stage?	pilots elsewhere?	standardization efforts?	devices/ chipsets	vendor shared services	piggyback on another tech?		one-tier	two-tier	multi-tier	Single	Multi	Agnostic
Geolocation and reservation	Database	deployed	yes	yes (802.11af, 802.22.1, ...)	n.a.	yes	yes	low	yes	yes	yes	yes	yes	yes
	Beaconing	pilots	yes (USA)	yes (802.22.1)	n.a.	yes	?	medium	yes	yes	yes	yes	yes	yes
	Blockchain	pilot (ANFR)	yes (ANFR)	?	n.a.	yes	yes	medium	yes	yes	yes	yes	yes	yes
Sensing	energy detection	mature	yes	yes	yes	n.a.	partly	low	possible	possible	possible	possible	possible	yes
	Time, frequency, and power sensing	mature (radar detection)	yes	yes (802.11a, 802.22.1, ...)	yes	n.a.	partly	medium	possible	possible	possible	possible	possible	yes
	Signal characteristics	mature	yes	yes	yes	yes (CBRS?)	partly	high	possible	possible	possible	possible	possible	no
	Space-based detection	research topic	yes	no	no	no	partly	high	possible	possible	possible	possible	yes	no
Transmission	Spatial sharing	research topic	no	no	no	no	yes (MIMO)	very high	yes	yes	unlikely	yes	yes	no
	Full-Duplex radio	research topic	no	no	no	n.a.	no	high	yes	yes	yes	yes	yes	yes
	Synchronisation	mature (4G/5G)	no (except licensed)	yes	yes	yes	yes (4G/5G)	low	yes	yes	yes	yes	yes	no
Decision making	AI/Machine learning	research topic	no	no	no	no	yes	high	yes	yes	yes	yes	yes	yes
Resource sharing	Virtualisation and infrastructure sharing	mature	?	yes (3GPP)	n.a.			medium	yes	yes	unlikely	yes	unlikely	no

Annex B Glossary and abbreviations

3GPP : Third Generation Partnership Project (which develops protocols for mobile technology)

4G : Fourth Generation (of mobile technology)

5G : Fifth Generation (of mobile technology)

6G : Sixth Generation (of mobile technology)

5G NR : 5G New Radio

5G NR-U : 5G New Radio Unlicensed

AFA : Adaptive Frequency Agility

AFC : Automated Frequency Coordination

AI: Artificial Intelligence

ANE : Agencia Nacional del Espectro (Colombia)

ANFR : L'Agence national des frequences (FR)

AP : Access Point

ASTRON : Netherlands Foundation for Research in Radio Astronomy

BS : Broadcasting Service / Base Station

CAB : Coordinated Access Band

CBRS : Citizen Broadband Radio Service

CBSD : CBRS device

C&C : Command & Control

CEPT : Conférence Europeènne des administration des Postes et Télécommunications

C-ITS : Cooperative Intelligent Transport Systems

CPI : Certified Professional Installer

CROC : Complementary Receiver Operating Characteristics

CSA : Concurrent Spectrum Access (also referred to as spectrum underlay)

CSMA : Carrier Sense Multiple Access

CSIR : Council for Scientific and Industrial Research (South-Africa)

CPAS : Coordinated Periodic Activities among SASs

CSS : Coordinated Spectrum Sharing / Cooperative Spectrum Sensing

DFS : Dynamic Frequency Selection

DLT : Distributed Ledger Technology

DoA : Direction of Arrival

DoD : Department of Defense

DOM : Detached Operation Mode

DPA : Dynamic Protection Area

DSA : Dynamic Spectrum Alliance (industry body) / Dynamic Spectrum Access

DSM : Dynamic Spectrum Management

DSS: Dynamic Spectrum Sharing

ED : Energy Detection

EIRP : Effectively Isotopically Radiated Power

eLAA : enhanced Licensed Assisted Access

eLSA : evolved Licensed Shared Access

EMC : Electro Magnetic Compatibility

eNB : Base Station

ESC : Environmental Sensing Capability

ETSI : European Telecommunications Standards Institute

EUDs : End User Devices

FCC : Federal Communications Commission (USA)

FD : Full Duplex

FDMA : Frequency Division Multiple Access

FeLAA : Further enhanced Licensed Assisted Access

FS : Fixed Service

FTTH : Fiber to the Home

GAA: General Authorised Access

GPS : Global Positioning System

GPU : Graphics Processing Unit

GSP : Generalised Matching Pursuit

ICASA : Independent Communication Authority of South-Africa

IEEE : Institute of Electrical and Electronic Engineers

IMT : International Mobile Telecommunications (commonly refers to a frequency band)

IoT : Internet of Things

ISM band : Industrial, Scientific and Medical band (unlicensed use)

ISP : Internet Service Provider

ITS : Intelligent Transportation Services / Intelligent Transport Systems

ITU-R : International Telecommunication Union – Radiocommunications

JD : Joint Detection

LAA : Licensed Assisted Access

LAT : Listen and Talk

LBT : Listen before Talk

LMA : Leased Management Agreements

LOFAR : Low Frequency Array (radio telescope)

LPI : Low Power Indoor – max 200 mW

LSA : Licensed Shared Access

LTE : Long Term Evolution

MAC : Medium Access Control

MIMO : Multiple Input Multiple Output

ML : Machine Learning

MNO : Mobile Network Operators

NIST : US National Institute of Standards and Technology

NRA : National Regulatory Authority

NR-U : New Radio for unlicensed spectrum

NTIA : National Telecommunications and Information Agency (USA)

OFDM : Orthogonal Frequency Division Multiplexing

OLFAR : Orbiting Low Frequency Array (radio telescope)

OSA : Opportunistic Spectrum Access (also referred to as spectrum overlay)
PAL : Priority Access License
PAWS : Protocol to Access White Space – protocol IETF RfC 7545
PL/PU : Primary Licensee / Primary User
PMSE : Program Making & Special Events
PPA : PAL Protection Area
PPDR : Public Protection and Disaster Relief
QoS : Quality of Service
RAN : Radio Access Network
R&D : Research and Development
RF : Radio Frequency
RSPG : Radio Spectrum Policy Group
SAMP : Sparsity Adaptive Matching Pursuit
SAS : Spectrum Access System / Spectrum Allocation Server
SC2 : Spectrum Collaboration Challenge (DARPA)
SINR : Signal to Interference plus Noise Ratio
SL/SU : Secondary Licensee / Secondary User
SOMP : Simultaneous Orthogonal Matching Pursuit
SSM : Spectrum Sharing Manager
TDD : Time Division Duplex
TDMA : Time Division Multiple Access
TDWR : Terminal Doppler Weather Radar
TOUGH : Telecoms Offshore User Group Holland
TPA : Training Program Administrator
TS : Two Stage
TSS : Two-Stage Sensing
TVWS : TV White Spaces
UHF : Ultra-high Frequency
U-NII : Unlicensed National Information Infrastructure
UWB : Ultra-Wideband
VLP : Very Low Power device – max 25 mW
VSAT : Very Small Aperture Terminal (satellite ground station)
VSP : Vertical Sector Player
WISPs : Wireless ISPs
WRC : World Radiocommunication Conference

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Annex D What is Spectrum Sharing

Many divisions and taxonomies are possible to break up the different flavours of spectrum sharing. This Annex aims to give a concise overview of spectrum sharing principles based on a simple one dimensional division: in 2014 the Wireless Innovation Forum has broken spectrum sharing into five distinct levels[17]. Although this report focusses on dynamic spectrum sharing, but for clarity and completeness here also a few examples for static spectrum sharing are given.

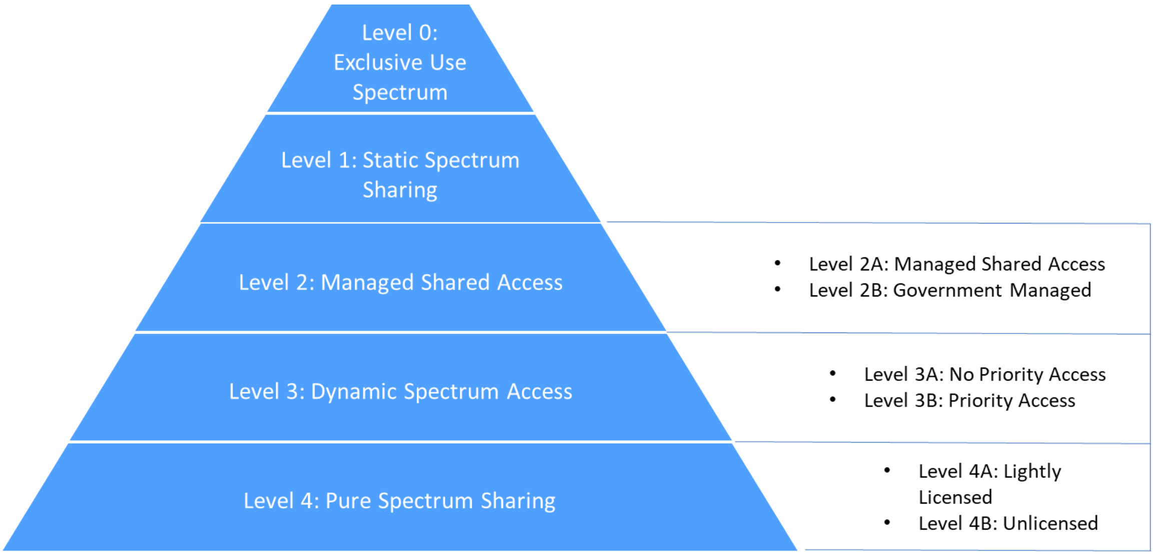

Figure 7: Five levels of spectrum sharing (Pucker, 2020)

- **Level 0: Exclusive Use –** Spectrum is assigned on an exclusive basis to a primary holder of spectrum rights (primary user) across the regulatory region.

  This establishes an incumbent, and can include, for example, cellular operators and radar installations. The expectation is that there is no interference.

- **Level 1: Static Spectrum Sharing –** Exclusive use spectrum is shared by primary users on a geographic basis, not a temporal basis.

  Examples: Geographically planned microwave link licenses, private-GSM/private-LTE licenses, taxi-dispatch per city, local (low power) FM-radio licenses spatially reused across the regulatory region.

[17] See: Annual report 2014 https://www.wirelessinnovation.org/assets/work_products/Reports/winnf-14-p-0001-v1.0%20dynamic%20spectrum%20sharing%20annual%20report%202014.pdf

- **Level 2: Managed Shared Access**
  - ◊ **Level 2A: Industry Managed –** Unused exclusive use spectrum in a specific location may be leased by the primary user to a 3rd party on a temporary basis (secondary user). Secondary users at this level are protected, exclusive users for the assigned period.

    Policies/Rules under which such arrangements can occur are set through negotiations between the primary and secondary users following regulatory requirements established for such activities, and such rules may require the secondary user to clear the spectrum under specific conditions should the primary user require the spectrum.

    Examples: Licensed Shared Access (LSA), Leased Management Agreements (LMA)

  - ◊ **Level 2B: Government Managed –** Exclusive use spectrum in a specific location may be assigned by a regulatory agency on a temporary basis to a 3rd party (secondary user). Secondary users at this level are protected, exclusive users for the assigned period. Primary users who are using the spectrum may be required to vacate for the assigned period.

    Policies/Rules under which the secondary user operates are set by the regulatory agency.

- **Level 3: Dynamic Spectrum Sharing**
  - ◊ **Level 3A: No Priority Access –** Spectrum access is non-exclusive. Spectrum held by a primary user that is not being utilised in a specific location and at a specific time is available for use by secondary users on a first come, first served basis so long as they do not interfere with the primary user. Such secondary use is unprotected, and the secondary user must vacate the spectrum when required by the primary user. There is a management function, via a database or other means, that ensures non-interference with the primary user, and such management functions may be used to support coexistence between secondary users.

    Example: TV Band Devices, 5 GHz U-NII

  - ◊ **Level 3B: Priority Access (3 Tier Model) –** Spectrum access is non-exclusive. Spectrum held by a primary user that is not being utilised in a specific location and at a specific time is available for use by a secondary user so long as they do not interfere with the primary user. Certain secondary users are assigned priority access privileges. Prioritisation can be made based on multiple models (cost based/micro auctions, public good, social factors/uses, fifo, etc.). Access by priority users is protected, while access by all other secondary users is not protected: priority users have first rights to available spectrum, and other secondary users must vacate if a priority user wishes access. There is a management function, via a database or other means, that ensures non-interference with the primary user, manages access by priority users, and such management functions may be used to support coexistence between secondary users.

    Example: 3.5 GHz Citizens Broadband Radio Service (CBRS)

- **Level 4: Pure Spectrum Sharing**
  - ◊ **Level 4A: Lightly Licensed –** Spectrum is not assigned to a specific primary user. Use of spectrum is protected while occupied. Rules may exist for length of time spectrum may be occupied.

    Example: US 3650 to 3700 MHz band

  - ◊ **Level 4B: Unlicensed –** Spectrum is not assigned to a specific primary user. Use the spectrum is completely unprotected, and is available to any network or user within limitations/rules/policies established for each band.

    Example: ISM bands

Annex E Interviews

i Interviewees

Along with the desk research overviewed earlier, expert interviews were conducted to assess the trends and experiences from the market. Along with the assigner, eight interviewees were selected, representing different aspects of the field of spectrum sharing. Amongst the interviewees were researchers on the subject, developers of wireless technologies and experts on critical services and ad-hoc frequency use. Most of the experts were based in The Netherlands, but were also familiar with the international market and trends. Experts from Belgium and the USA also took part in the interviews. For the sake of anonymisation, this report only lists the overall findings from the interviews and not the opinions from each individual.

The following experts were interviewed for this study:

Prof. dr. ir. Ingrid Moerman, IDLab, Ghent University

Professor dr. ir. Ingrid Moerman leads the the research and education in the area of mobile and wireless communication networks at IDLab (Internet Technology and Data Science Lab) research group at Ghent University. With her group she has won research grants from the DARPA Communications Challenge. This DARPA challenge focused in particular at frequency reuse and advanced dynamic spectrum sharing techniques.

Preston Marshall, Google, CBRS and SAS

Preston Marshall is responsible at Google for its CBRS and SAS system. He is the Chairman of the CBRS Alliance, recently rebranded into OnGo Alliance and the co-chair of the Spectrum Sharing Committee (CBRS Standards) at the Wireless Innovation Forum.

Dré Klaassen, consultant & PMSE sector expert

Dré Klaassen was a musician, while studying mathematics and physics and ended up in the audio-industry. He is a (regulatory) consultant in the realm of Program Making and Special Events sector. He was from 2010 – 2014 the President of the Association of Professional Wireless Production Technologies and has worked before at Sennheiser and Audio-Technica in the realm of wireless production tools for professional events / stage & studio’s.

Prof. dr. ir. Mark Bentum – Eindhoven University, ASTRON-OLFAR

Mark Bentum is a Full Professor in Radio Science with the research group Electromagnetics at the TU/e department of Electrical Engineering. He is also affiliated with the Netherlands Foundation for Research in Radio Astronomy (ASTRON), where he is head of the radio group. His main research interest is in radio astronomy, particular in low frequency radio astronomy. He is the initiator of the OLFAR project, the Orbiting Low Frequency Antennas for Radio astronomy. OLFAR is a space-based radio telescope to observe the sky at frequencies below 30 MHz consisting of many small satellites.

At TU/e his work focuses on various aspects of this radio telescope, such as the antenna systems, the calibration of the array, the clocking and synchronisation of all the elements, localisation, interference mitigation and the signal processing aspects of the telescope.

Herman van Sprakelaar – Netherlands national police force

Herman van Sprakelaar has worked in mission critical telecommunications for the Dutch police forces since 1997. Since 2012 he has been involved in the development and migration to the successor of the Dutch national C2000 TETRA network for emergency services, and active in standardisation of mission critical technologies at the TCCA.

Hans van Leeuwen, Sostark

Hans van Leeuwen is the owner of (chipset) technology developer Sostark, operating in the Netherlands, Singapore and Santa Clara USA. He specialised in: Digital Audio, Wireless Audio, wireless IoT, IEEE802.15.4, ZigBee, IP500, Low Power Wireless products, Wi-Fi, sensor networks, Building Automation

Van Leeuwen has developed the chipset for the first commercial Wi-Fi (802.11b) PCMCIA card, and hifi quality wireless headphones used by Consumer Electronics firms, wearables like smart RF-wristbands for festivals, recently repurposed for a privacy aware corona-tracker. He recently started producing for white space products via his Singapore operation.

Peter Koomen, IP2 Solutions

Peter Koomen is a regular development partner of Sostark. Koomen, with his firm IP2 Solutions, develops an infrastructure line for mesh products and antennas. He has a background as microwave engineer with development in high frequency hardware design and radar technology, and has developed products for supermarkets (self-scanners), electric bicycles.

Marnix Vlot, NXP

Marnix Vlot is the Standardisation Business Partner at NXP (Semiconductors). He manages the overall standardisation program, standard bodies memberships and IPR rules efforts. NXP as one of the largest chipset manufacturers in the world develops, manufactures and markets a broad range of RF-chipsets.

Willem Blom and Karen Blanksma, Schiphol

Willem Blom and Karen Blanksma are Advisors Ethercontrol and Radiocommunication at Royal Schiphol Group. Royal Schiphol Group operates several airports in the Netherlands and participates in (terminals at) airports abroad incl. JFK Terminal 4 in New York. Its largest activity is operating Amsterdam Airport Schiphol, Europe's leading airport by flight movements and third largest in passengers [ACI][18]

[18] https://aci.aero/news/2020/05/19/aci-reveals-top-20-airports-for-passenger-traffic-cargo-and-aircraft-movements/

ii Interview structure

The interviews followed a semi-structured approach of approximately an hour long. Along with more general questions, each interviewee was asked questions that were specified to their respective fields. Due to this, an extensive overview of the current market and future expectations for spectrum sharing was achieved. Below, a concise overview with the key observations is presented.

iii Findings and assessment

Electro Magnetic Compatibility (EMC)

Several of the interviewees emphasised on problems with interference from other electromagnetic sources. These problems include, but are not limited to, (background) noise and spurious emissions. Sources of interference are objects like solar panels, LED displays and electric car chargers. Several of these objects seem to cause problems, particularly in the UHF frequencies for emergency services. If several of these objects come together in one place, for example a mall, it hinders broadcasting and sensing. Interference like this also severely hinders satellites that measure in a broad frequency range. The latter is accounted for with rules and regulations that forbid the use of solar panels, windmills or mobile communication in certain areas. As such, dynamic spectrum sharing will not likely be an option in those areas. Sharing based on Time Division Multiple Access was noted as an option. Another trend that increases interference is the wider availability of drones. These interference issues hinder for example the use of Ultra Wide Band, especially for critical services. Another problem that became clear during the interviews is the possibility of intermodulation, which is highly problematic for the PMSE sector.

Small use case for ad hoc networks

While the application of CBRS in the USA incorporates the prioritising of emergency services, there does not seem to be a use case for ad hoc networks for emergency services in The Netherlands. This is due to the shift of this sector towards the use of public operator networks. This might incorporate sharing. Major events that heavily rely on mobile communications are pre-planned events and thus do not necessarily need the potential to suddenly increase the range on which to communicate. Due to security reasons, sharing also seems to be problematic. This is also the case for the events-sector, as for example music artists require the most reliable option for their communication. This is not only due to the expectations of the live audience, but also due to the timecode nature of many shows and the stress that interference during a performance induces. Thus, spectrum sharing is not considered a valid option.

Use of frequency coordination/ether control

Currently, events with involve a lot of mobile communications and frequencies ‘in the air’ require a frequency coordinator, which is usually a (team of) professional(s). It was noted by an interviewee that big productions easily have more than 100 frequencies ‘in the air’, which isn’t easily coordinated digitally. Digital coordination might also result in problems with latency, compression and power. Places that are known to rely a lot on communication and frequently experience interference, like airports, also have an appointed ether controller. Every interviewed party that has experience with a function like this notes that it is not likely that this function will be replaced with AI anytime soon. Dynamic spectrum sharing however might rely on databases and coordinated with AI-like technologies (as was noted by researchers on the subject). As such, it is unlikely that named events and places will yet change their current practices to make way for spectrum sharing, while a different use of spectrum may possibly benefit them the most. There are also questions about the economic feasibility of changing to digital frequency coordination.

Dominance of 5G

Many interviewees mentioned a strong dominance of (developments toward) 5G, specifically in Europa. This is for example seen in developmental trajectories of large manufacturers both for chips and devices. This poses as challenge as the focus on 5G may hinder the willingness to work on spectrum sharing solutions. Not all interviewees noted the focus on 5G. The emergency services sector for example just longs to a robust standard, whether it is 5G or another solution.

Problems with centralisation

It was noted that central databases for coordinating spectrum sharing may pose a latency problem. Dynamic spectrum sharing, especially with prioritising mechanisms, rely on highly responsive databases or other means to prioritise its users. This problem can be solved by additionally developing decentralised or localised decision making. These technologies are already in development and are tested. These tests featured communication between devices by a 'bus protocol' and sensing. Decentralised coordination is thus already a valid option. The challenge however is to get incumbents like mobile operators on board, as they most likely prefer to have central control. This is however more an organisational challenge, which is elaborated on later on. Examples of sectors that are affected by latency problems are the automotive industry, the events sector (audio) and the gaming industry.

The benefits of an 'innovation policy'

A topic during the interviews was the opportunity for innovation within the current regulated spectrum which is nihil. Incumbents do not see the value in breaking up this status quo. While spectrum sharing is a means to lighten the burden of the radio spectrum planning and combat scarcities, incumbents might not see the value in that. Regulators such as Ofcom and ANFR recognise this problem, and the opportunities spectrum sharing can provide to support innovation. Ofcom published in 2015 a framework for spectrum sharing and followed up with more options for shared spectrum use[19]. In France the ANFR has taken part in Station F, the biggest global start-up campus located in Paris. The USA tackled this problem and enables innovation by providing parties an opportunity to start small with investments, by introducing CBRS. This provided a scalable solution without large prior investments. Another example of more flexible spectrum assignment that led to innovative technologies is Wi-Fi. The opportunity to get into the spectrum market without the costly early investments resulted in a bottom up, market led development of the spectrum. To ensure a reliable system, multi-array (virtual) databases are used. RF-certificates are used to provide trust, which is a necessity according to one of the interviewees. Trust prevents that all will fall back on the existing systems when inevitable (small) issues occur.

Problems with standardisation

There are certain problems of a more technical nature that are not easily solved by spectrum sharing. Examples are 'standards races' for technologies that are still developing, for example in the automotive industry. Unlicensed bands and spectrum sharing make it easier to develop different technologies within the same frequency, but make it harder to regulate new (necessary) standards. Another technical issue is that of legacy. Certain technologies that are currently in use and interfere with upcoming technologies are hard to get rid of, while they hinder innovation and sharing of spectrum. Another legacy problem is the use of chipsets that will be outdated if spectrum sharing is introduced. Certain sectors, like the emergency services, need a reliable network and may thus be hesitant to make the switch towards spectrum sharing. They are also unable to use both technologies if this means they have to switch between devices. It is unclear how spectrum sharing will be incorporated in their day-to-day jobs.

[19] https://www.ofcom.org.uk/__data/assets/pdf_file/0032/79385/spectrum-sharing-framework.pdf

Other sectors that note possible problems with standardisation are sectors that operate internationally. The event sector notes that not all organisations and countries are willing to share information concerning frequencies in use, which results in unexpected interference and noise. For boundary-crossing events, like the Tour de France or touring musicians, sharing a spectrum might not be possible if the technology is not adopted by neighbouring countries. Airports also foresee problems with international standardisation.

Access to centralised databases

Another issue is related to the Internet-of-Things (IoT). This development will further crowd the frequency spectrum, while it poses a problem for spectrum sharing. In a way, spectrum sharing will incorporate communications between different devices to ensure that a certain bit of the spectrum is open for communications. It was mentioned that certain devices that are (going to be) part of the IoT might lack this feature. This is especially the case if spectrum sharing is coordinated by a centralised database, as this will require an internet connection. Another option is localised decision making, which also requires devices to have certain features. Both methods are rather costly. This issue is also apparent in the automotive industry, as it is unclear how cars stay up-to-date. This results in questions around accountability, in case something goes wrong.

Upon that, centralised databases might not provide a full solution to interference problems. One of the interviewees referred to a Danish example where a webtool that should show usable frequencies, but did not perform as users were still able to pick up unidentified signals. Sensing might solve this problem, but was also said to be unreliable at times.

Organisational vs technological effort

While the introduction of dynamic spectrum sharing will also involve some technical efforts, most interviewees emphasised the organisational effort. The hardest challenge might be to gather the various stakeholders and to get them all on the same page. In the current status quo, most parties involved have a defined dedicated spectrum and feel like they lose control if a switch towards spectrum sharing is made. They are not yet fully aware of the necessity and are adamant on protecting their current incumbent position. Upon that, they are unsure about the reliability of a shared spectrum. Incumbents thus have to be convinced that spectrum sharing also benefits them, for example if machine learning tools are used to predict their behaviour and protect them from interference. Other interviewees also expected organisational problems on the user-side. On of the perceived obstacles is managing a spectrum database, which was expected to be an organisational problem, rather than a technical problem.

In the USA, CBRS worked due to a competing, but totally coordinated model. This is shown by the way they organise their database, which is a virtualised centralised database. It is multiple array, but operates as a single database, which keeps being updated and thus synchronised. Behaving as a single entity, but differing in service and rates provides a market-driven spectrum.

Annex F DSS examples

Paragraph 3.3 of the main text mentions a number of example implementations of Dynamic Spectrum Sharing. This Annex provides some details for each of the examples.

Television Broadcasting shared with Public Safety Land Mobile

In major US markets, the 450-470 MHz UHF band used for private land mobile services is heavily congested. The UHF television band begins with Channel 14 at 470 MHz. One to three 6 MHz channels between 470 and 512 MHz are made available to public safety users for additional land mobile use in 13 markets, generally allowing base stations within an 80 kilometre radius of a designated point and mobile operation within 48 kilometres of their base station. Thus the total radius is 128 km. This is referred to as "T-band". An act of Congress several years ago instructed the FCC to withdraw this and auction the spectrum to mobile carriers. This is lower in frequency than desired by most mobile carriers and the channels are narrower than currently desired, limiting that demand. At the same time many public safety agencies claim that they do not have suitable alternatives. Thus there is considerable pressure to retain T-Band.

TV-White Space (TVWS)

White spaces are geographic regions where a particular spectrum is temporarily or for a long period of time not used by a recognised or licensed service or application. The concept originated from the sharing of unused TV broadcasting channels (VHF and UHF bands), in particular geographical areas. It originated from the US.

Television broadcast channels not in use in a given area are available, under very strict limitations, to be used for other purposes. This so-called TV White Space is available for both broadband data applications and for wireless microphones. In the latter case, wireless microphones operated by licensed broadcasters are given priority as a licensed service. Licenses are also available to venue operators and sound contractors that use 50 or more wireless microphones as an "integral part" of their productions.

Over-the-air television broadcasting in the United States is divided into three distinct frequency bands. All channels are 6 MHz wide. VHF-low channels 2-6 occupy 54-88 MHz (with a gap at 72-76 MHz). VHF-high channels occupy 174-216 MHz. UHF channels were originally numbered 14-83, after refarming for mobile use, only UHF TV channels 14-37 remain, with Channel 37 reserved for radio astronomy.

Licensed wireless microphones operate on TV channels on a secondary basis, which puts them at a higher priority than unlicensed users. Mediation is done via a database. Licensed wireless microphones register their locations in the database, which white space devices, licensed and unlicensed, must check daily to determine which channels are available at their location. Broadcast station channels do not change frequently; the time between checks is based on the needs of licensed wireless microphones, which may move to a new location at any time. Typically a wireless microphone system's base unit queries the database, while the microphones get permission via that base unit.

While at one point the FCC had proposed reserving a channel for wireless microphone use, the repacking of channels was designed to ensure that at least one channel remained available for wireless microphones everywhere in the country.

Wireless microphones and other portable/mobile devices, whose power output is generally limited to 40 mW, are also allowed to operate in the duplex gap in the middle of the 600 MHz band and in the 3 MHz guard band above Channel 37. They are allowed 100 mW on other channels where the database allows it.

Unlicensed broadband TV White Space devices are much less common, with only a few thousand registered in the database. Microsoft's AirBand initiative has not had much success in promoting it. Largely this is likely a result of the onerous technical requirements imposed on such devices, such as requiring

55 dB suppression of emissions into the adjacent channel. The database also allocates channels using strict protection criteria that make worst-case assumptions about potential interference to every TV station's protected contour. Even adjacent channels may not be used for these higher-powered (1 watt conducted) devices, and thus most urban areas and major markets have no channels available for this class of white space device.

A special case applies to the 600 MHz band, which was transferred from TV to mobile use. Unlike other licensed mobile bands, a limited degree of opportunistic use is still permitted. TV White Space devices may operate on these formerly-TV channels if they are far enough from a mobile licensee's base station.

While the database operation is nominally competitive, several early entrants have exited the market, and the only TVWS database still operating for the United States is WaveDB, operated by the French firm Red Technologies, which acquired it in 2020 from the UK's Nominet.

In the realm of TV White Spaces activity has also been noted in developing countries, in particular in Africa and Latin America.

In South-Africa a program has been launched under supervision of CSIR, the Council for Scientific and Industrial Research (Department of Science and Innovation). https://whitespaces.meraka.csir.co.za/

They offer a Calculation Engine Service, while regulator ICASA (Independent Communication Authority of South-Africa) engages in Type Approval. Registration in a database for secondary use is obligatory, but use is License Free.

South Africa is running a trial since August 2020 using the Protocol to Access White Space (PAWS) - IETF Request for Comment 7545. They expect commencement of service from April 2021. A range is claimed of 30 km, while 8 MHz channels are used.

In Colombia a database is established but not yet automated by radio agency ANE (Agencia Nacional del Espectro). Until automation is introduced, they assign lease periods of 6 months, which will go down to 24 hours periods. The claimed range is up to 15 km using 6 MHz white space channels.

For the calculations they follow the method according to Recommendation ITU-R P1546-6.

An assessment of the other countries mentioned reveals a focus on rural broadband internet and typical capacities are 7 to 10 Mbps for download and upload for a White Space channel.

In Europe TVWS didn't find much traction, also the current situation in East and South-East Asia don't show the actual appetite being what was expected in the period 2013 – 2017.

The United Kingdom established a database and in Ireland we found a trial from Teagasc, agriculture and food development authority for 'challenging terrain' with no line of sight and focused on Mobile hotspots, Rural Internet and Farmbeats a sensor platform to collect (weather data).

While data rates were in the range of 7 – 9.2 Mbps, the distances were much shorter: up to 3.2 km.

TVWS in Europe has been qualified as not that attractive. The rapid extension of mobile cellular networks (4G) into rural areas, has provided high bandwidths with more affordable end-user devices like LTE home routers (€ 119 retail[20]), than the typical price points seen for TVWS (manufacturer Adaptrum touts their TVWS CPE as starting from US$300).

[20] https://www.idealo.de/preisvergleich/OffersOfProduct/200158018_-fritz-box-6820-lte-v3-avm.html

Projects with TVWS in developed countries like Singapore launched with great enthusiasm in 2013, and three operators established geo-location database providers stepped in[21], and Machine-2-Machine projects were listed. However recent new trials with sensors indicate TVWS is considered "underused"[22]. It didn't quite take off as expected in 2013/2014.

Our impression is that outside serving rural broadband in countries with a large set of infrastructure challenges TVWS in most countries can be classified as a technology still searching for an application.

- **Authorisation regime**: licensed
- **Frequencies**: VHF and UHF
- **User hierarchies:** Two-tier system: PUs, e.g., and SUs
- **Radio technologies:** Technology agnostic. PU radio technologies could be anything, e.g., TV, radar, satellite, etc. The SU radio technologies can also vary, e.g., LTE, 5G NR, etc.
- **Spectrum access policy**: Opportunistic spectrum access.
- **Spectrum usage-status acquisition:** Commonly a geolocation database is used. Could also be based on beaconing and be augmented with sensing.
- **Spectrum-sensing metrics:** If sensing would be used the sensing metric would best depend on the nature of the PUs, e.g., cyclo-stationary signal detection in case the PU is a sweeping radar transmitter.
- **Status:** Standardised (IEEE, IETF, ECMA) and deployed.

Licensed Shared Access (LSA)

The LSA is a framework to share spectrum between a limited number of users.

The PUs (incumbents) share their spectrum with one or several PUs in accordance with a set of static (e.g., exclusion zone, operation time restrictions) or dynamic (e.g., time-sharing, on-demand) conditions defined by the regulator.

LSA ensures a predictable QoS for all spectrum use rights holders, network operators and consumers. Individual authorisations with explicit sharing agreement to ensure the protection of the PUs, taking into account operational requirements, are granted to terrestrial MNOs in bands used by other type of PUs.

The implementations are based on an LSA Repository, a geodatabase populated by input from the incumbents and a central LSA Controller, that communicates with the OA&M of each participating MNO, processes spectrum requests, and decides on the allocation of spectrum to the LSA licensees on the basis of the data in the LSA Repository.

ETSI has produced a specification in 2017.

- **Authorisation regime**: licensed
- **Frequencies** 2.3-2.4 GHz primarily terrestrial, but also other IMT bands, and considered for 3.6 GHz, 26 GHz bands for satellite-terrestrial sharing
- **User hierarchies** Two tier system: incumbents, e.g., telemetry, military, satellite or an MNO, and licensees, typically MNOs
- **Radio technologies:** The principle is technology agnostic. Implementations and pilots with LTE and satellite radio. 5G NR in the future.
- **Spectrum access policy:** Cooperative transmission, centrally coordinated.
- **Spectrum usage status acquisition method:** Geolocation database fed by incumbents (usage) and NRA (policy)

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[21] https://www.imda.gov.sg/regulations-and-licensing-listing/spectrum-management-and-coördination/spectrum-planning/tv-white-space

[22] https://www.tech.gov.sg/media/media-releases/govtech-sla-caas-to-trial-tv-whitespace-connectivity

- **Spectrum-sensing metrics**: not applicable
- **Status:** Standardised (ETSI, 3GPP Release 14) and various testbeds and pilots.

Evolved Licensed Shared Access (eLSA)

The main differences between eLSA and LSA are that it is designed for local environments, e.g., Industry 4.0, AV content production, PMSE, public protection and disaster relief (PPDR), e-health, 5G micro-operators, etc. by offering new access models:

- Local area licensing (to local networks) by NRA from the eLSA Repository:
- Leasing or subleasing by incumbent MNOs to vertical operators.
- Spectrum as a service: an incumbent MNO provides infrastructure, spectrum and interference management to local networks of vertical operators, e.g., using 5G network slicing.

It introduces Detached Operation Mode (DOM) for verticals to allow them to temporarily operate without a permanent network connection to the eLSA System.

It has a distributed eLSA controller architecture (controller entities in the vertical's domain) allowing both faster decision-making and less control overhead resulting in better dynamics of sharing than is the case for LSA.

ETSI has produced a specification in 2020.

- **Authorisation regime:** licensed
- **Frequencies:** sub 6 GHz IMT bands
- **User hierarchies** Two tier system: primary users, e.g., MNOs, and secondary users, called vertical sector players (VSP), e.g., a factory.
- **Radio technologies**: radio-technology agnostic except in spectrum-as-a-service (see below), where the radio-technology of the MNO is used, e.g., 5G-NR.
- **Spectrum access policy**: cooperative transmission, centrally coordinated.
- Spectrum usage status acquisition method: geolocation database fed by incumbents (usage), VSPs and NRA (policy)
- **Spectrum-sensing metrics**: no sensing function, but the method could be augmented with sensing input as proposed by the EU project ADEL.
- **Status:** Standardised (ETSI) and testbed experience (ADEL project)

Licensed-Assisted Access (LAA), Enhanced LAA (eLAA) and Further-enhanced LAA (FeLAA)

LAA/eLAA and FeLAA are about cellular operation in unlicensed bands, by combining a carrier in licensed spectrum with a carrier in unlicensed spectrum, using carrier aggregation. The incumbents (e.g., Wi-Fi) operate as before. The operation of the cellular users is strictly scheduled by the the base station (eNB) which detects, via carrier sensing, when transmission opportunities arise and subsequently accesses the medium, using the same MAC as the legacy users. There is no contention between the cellular users, since they are strictly scheduled. However fair contention happens between cellular and incumbents and between the incumbents themselves (as before sharing). LAA is standardised by 3GPP. 3GPP Release 13 only applies to the downlink (base station to UE). In Release 14 (2017), this was extended to the uplink (UE to base station), under the name Enhanced LAA (eLAA) and in Release 15 (2019), Further-enhanced LAA (FeLAA) was introduced to allow for autonomous, i.e., grant-free uplink transmissions.

- **Authorisation regime**: unlicensed
- **Frequencies:** the 5 GHz band is the primary target, but shared spectrum bands, in particular the CBRS band at 3.5 GHz, are also of interest.
- **User hierarchies:** no hierarchy, equal opportunities for legacy users and cellular users.
- **Radio technologies:** the same physical layer is used by all participants. The eNB has the same MAC to secure transmission opportunities (slots) for the cellular users.
- **Spectrum access policy:** cooperative transmission, distributed coordination.

- **Spectrum usage status acquisition method:** geolocation database fed by incumbents (usage), VSPs and NRA (policy)
- **Spectrum-sensing metrics:** no sensing function, but the method could be augmented with sensing input as proposed by the EU project ADEL.
- **Status:** Standardised (ETSI, 3GPP Releases 13, 14 and 15) and deployed.

MulteFire

MulteFire is a cellular technology (LTE-based) that operates in unlicensed spectrum standalone, i.e., without requiring a licensed carrier like in LAA. It is intended for non-conventional operators that do not possess licensed spectrum, e.g., private networks for industrial IoT, neutral host networks, etc. It has a roadmap to future solutions based on 5G NR-U. It is technically similar to LAA and uses CSMA/CA to guarantee coexistence with Wi-Fi and LAA/eLAA networks. Furthermore, its uplink capacity is duty-cycle limited in the EU.

MulteFire requires devices that conform to the MulteFire Alliance industry-wide specifications.

- **Authorisation regime**: unlicensed.
- **Frequencies**: 800/900 MHz band for NB-IoT, 2.4 GHz band for U-eMTC (e.g., factory automation, asset management, surveillance monitoring), 5 GHz and 1.9 GHz DECT band for indoors (Japan), with DECT coexistence, for industrial IoT and enterprise use cases.
- **User hierarchies**: no hierarchy.
- **Radio technologies**: LTE, Wi-Fi, LAA/eLAA/FeLAA
- **Spectrum access policy**: cooperative transmission, distributed coordination, similar to LAA/eLAA.
- **Spectrum usage status acquisition method**: sensing at the BSs, sensing at the device for Wi-Fi
- **Spectrum-sensing metrics**: energy detection.
- **Status**: standardised (MulteFire Alliance) and deployed.

5G NR-U

3GPP Release 16 (July 2020) has defined NR-U: cellular operation in unlicensed spectrum. It is an evolution of LAA, eLAA and FeLAA and also intends to supersede CBRS. It is aimed at private cellular networks for enterprises, vertical industries, indoor networks, small cells for MNOs, fixed wireless access in the US and neutral host infrastructure. For private networks, it can be integrated with (wired) time sensitive networking for, e.g., industrial applications. It supports 5G features, e.g., wideband carriers, flexible numerologies, beamforming and dynamic TDD, where the uplink-downlink allocation may change over time to adapt to traffic conditions, etc. Two deployment scenarios are foreseen: NR-U anchored, i.e., carrier aggregation with a carrier in licensed spectrum, and standalone NR-U, without use of licensed spectrum.

To guarantee fair coexistence with IEEE 802.11 and LAA/eLAA, NR-U channel access is based on the listen-before-talk principle, like in LAA. However, since this access technique leads to inefficiency (percentage of time a frequency is not used, while there is demand) under high traffic load, coordinating transmissions between radio-heads (BS) is considered.

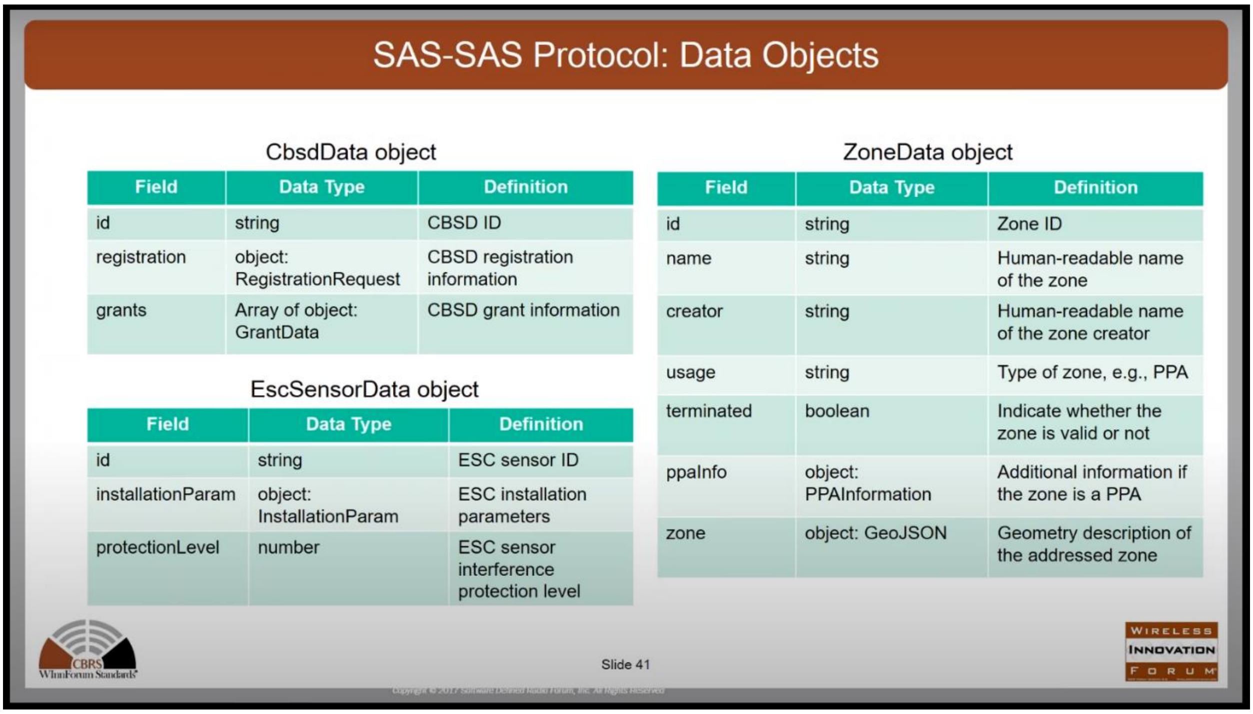
- **Authorisation regime**: unlicensed.
- **Frequencies**: 3.5, 5 and 6 GHz bands and mmWave bands up to 71 GHz.
- **User hierarchies**: No hierarchy, equal opportunities for Wi-Fi, LAA and 5G NR-U cellular users.
- **Radio technologies**: 802.11, LAA and NR-U
- **Spectrum access policy**: cooperative transmission, distributed coordination.
- **Spectrum usage status acquisition method**: sensing
- **Spectrum-sensing metrics**: energy
- **Status:** standardised (3GPP Release 16) and deployed.

Citizens Broadband Radio Service (CBRS)

The FCC established the Citizen Broadband Radio Service (CBRS) for shared use of the 3.5 GHz band by wireless broadband indoor and outdoor, ensuring interference protection and uninterrupted use by the incumbents. A three-tier sharing system is defined:

- Incumbents: military radar, satellite ground stations, and wireless ISPs (temporarily), protected from interference from the lower tier PAL and GAA users.
- Priority Access License (PAL) licensed users: the next highest priority access and protected from GAA users, e.g., PMSE and verticals.
- General Authorised Access (GAA) users: unlicensed and can use any portion of the 3.5 GHz band not assigned to higher tier users. Potential interference between GAA users is not regulated.

A key element of the CBRS architecture is the cloud-based Spectrum Access System (SAS), containing a geo-database of all PAL or GAA base stations, including, e.g., whether they are PAL or GAA users and their activity. It allocates and deallocates spectrum to PAL or GAA networks, based on RF density and channel availability using terrain and radio propagation data. The SAS also uses sensors known as the *Environmental Sensing Capability* (ESC), deployed in particular locations, e.g., near coastal radars, to detect incumbent activity and mitigate possible interference to incumbents. Figure 8 illustrates the types of data exchanged between SAS operators.



SAS-SAS Protocol: Data Objects

CbsdData object

Field	Data Type	Definition
id	string	CBSD ID
registration	object: RegistrationRequest	CBSD registration information
grants	Array of object: GrantData	CBSD grant information

EscSensorData object

Field	Data Type	Definition
id	string	ESC sensor ID
installationParam	object: InstallationParam	ESC installation parameters
protectionLevel	number	ESC sensor interference protection level

ZoneData object

Field	Data Type	Definition
id	string	Zone ID
name	string	Human-readable name of the zone
creator	string	Human-readable name of the zone creator
usage	string	Type of zone, e.g., PPA
terminated	boolean	Indicate whether the zone is valid or not
ppaInfo	object: PPAInformation	Additional information if the zone is a PPA
zone	object: GeoJSON	Geometry description of the addressed zone

Figure 8: Examples of data-objects exchanged between SAS-operators (source: WInnForum)

- **Authorisation regime:** mixed licensed and unlicensed
- **Frequencies:** 3.5 GHz CBRS band.
- **User hierarchies**: three-tier system: incumbent, PAL and GAA.
- **Radio technologies:** 4G LTE and later 5G NR-U
- **Spectrum access policy:** central coordination by SAS.
- **Spectrum usage status acquisition method**: sensing and geo-database
- **Spectrum-sensing metrics:** signal characteristics, e.g., matched-filter detectors, matched to the in-band radar system
- **Status:** standardised (WInnForum) and deployed.

Wi-Fi 6E and 6 GHz sharing

A far more promising approach is the April 2020 decision by the FCC to open the entire 6 GHz band[23] for shared spectrum in outdoor situations, which overlaps with the decision in Europe to allocate part of this band, 5.925 – 6.425 GHz band for Wi-Fi6E.

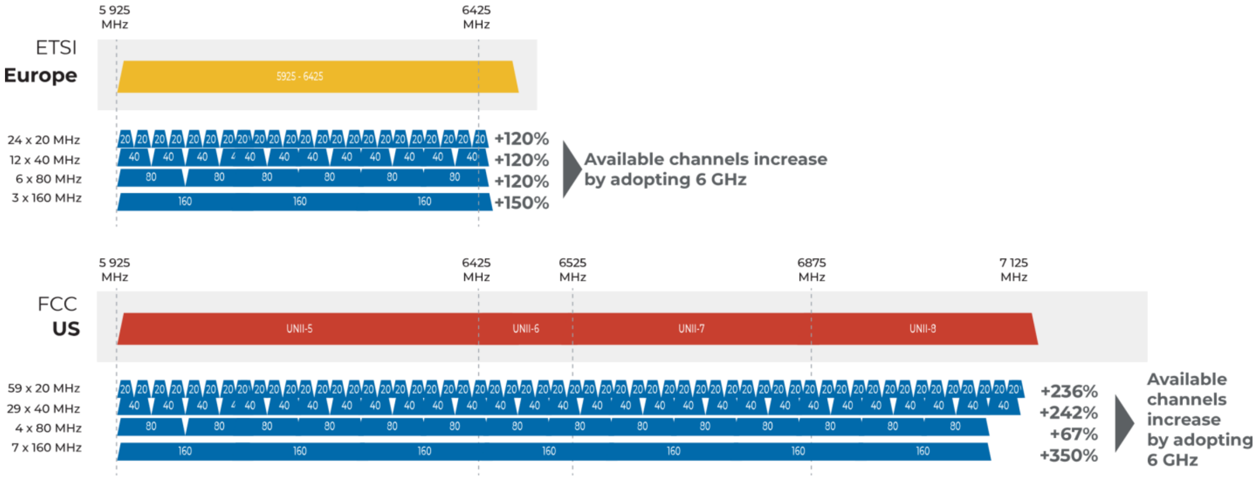


Figure 9: Different channel configurations in 6 GHz range in Europe and the USA [Source: Celeno]

In Europe, including the Netherlands, we found existing (long-distance) microwave links in the range from 5.925 – 7.125 MHz. Hence a discussion between primary and secondary use and "Automated Frequency Control" will also be needed in Europe. In particular the announced studies / questionnaires for WRC23, where for Europe it is foreseen that (unlicensed) IMT will be discussed for 6.425 – 7.125 GHz opens additional debates for sharing with microwaves and dynamic spectrum sharing database solutions like enhanced LSA (eLSA).

In the Netherlands there are currently two major users of microwave links in the 6 GHz band:

- TOUGH, the user group for North-Sea off-shore oil platform operators, who have recontracted their network in 2018 to Tampnet A.S. Links landing from oil rigs at radio towers in The Hague, Den Burg (Texel) and West-Terschelling operate in the 6 GHz
- Broadcast Partners, who uses 6 GHz microwaves across the Netherlands to distribute FM- and DAB-programs from the studios to the radio transmitters they operate for various FM commercial radio broadcasters.

Where the French regulator also mentions the existence of 6 GHz Fixed Satellite Service ground stations (uplinks), it is an indication, that dealing with 6 GHz (dynamic spectrum) sharing, whether it is Wi-Fi6E or an IMT version, will require serious consideration and probably some trials / pilots too.

Emmanuel Faussurier from ANFR (France) explained at the WInnForum conference on 6 GHz RLANs:

European regulations for 6 GHz RLANs are under final adoption phase, limited initially to LPI (Low Power Indoor) and VLP (Very Low Power) devices:

- LPI : 5945-6425 MHz with max 23 dBm and CDC
- VLP Category A: 6025-6425 MHz with max 14 dBm
- VLP Category B: 5945-6425 MHz with max 14 dBm and CDC

Concept of *Country Determination Capability* (CDC) is introduced in draft regulations adopted by ECC for public consultation (July 2020):

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[23] https://www.fcc.gov/document/fcc-opens-6-ghz-band-wi-fi-and-other-unlicensed-uses

- The CDC functionality shall enable a device to determine whether the use is allowed or not allowed in a Member State and to operate accordingly France is supporting a geolocation database sharing model as a win-win solution:
- Outdoor applications are clearly incompatible with FS but may address some useful niche market (e.g. wireless camera, internet access in remote areas…)
- Need for ETSI harmonised standard to include features such as geolocation capability, database discovery capability, common interface for data exchange between devices and databases etc.

ANFR expects still a lot of work to do by them and other European radio agencies to implement the introduction of the 6 GHz devices on the market.

- **Authorisation regime:** mixed licensed and unlicensed
- **Frequencies:** 6 GHz band.
- **User hierarchies**: three-tier system: incumbent, PAL and GAA.
- **Radio technologies:** Wi-Fi6E
- **Spectrum access policy:** central coordination, automated frequency control
- **Spectrum usage status acquisition method**: geo-database
- **Spectrum-sensing metrics:**
- **Status:** proposed, not yet implemented.

Coordinated Spectrum Sharing (CSS)

Coordinated Spectrum Sharing (CSS) is a "greenfield" concept, developed by Samsung Research, to provide extra capacity for MNOs through offloading to shared unlicensed spectrum and enable non-traditional operators (verticals) without the need for exclusive licenses. It targets bands without incumbents, e.g., the CBRS 3.5 GHz bands, but also others (up to 3 THz). It uses dynamic coordination between base stations (BS or eNB) belonging to different MNOs, eliminating the need for CSMA/CA based channel sensing, thereby increasing the sharing efficiency. Spectrum sharing happens at the level of transmission bursts (ms level) and is therefore able to use much more capacity than other longer-timescale based methods (e.g., LAA, CBRS). Besides the coordinated access opportunistic access, using carrier sensing, is still an option under particular circumstances. Coordination among BSs is done by a Spectrum Sharing Manager (SSM), residing in the core network or distributed among the BSs. It does resource (frequency and time slots) reservation and allocation on request of the BSs based on the interference relationships between the BSs, derived from sensing by the BSs. CSS can be considered as a beyond-5G concept. It does not yet appear in the 3GPP roadmap.

- **Authorisation regime**: unlicensed.
- **Frequencies:** unlicensed spectrum without incumbents, up to 3 THz.
- **User hierarchies**: a multi-tier system. Within the top tier various degrees of prioritisation can be imposed by the Spectrum Sharing Manager, from fair sharing to hard priorities. The lower tier is intended for opportunistic access.
- **Radio technologies:** requires an unspecified slotted PHY layer, conforming to the CSS design.
- **Spectrum access policy:** cooperative transmission, centrally coordinated at the transmission burst level for the top tier; opportunistic access for the lower tier.
- **Spectrum usage status acquisition method**: sensing at the BSs.
- **Spectrum-sensing metrics**: energy detection.
- **Status**: research concept and simulations.

DARPA Spectrum Collaboration Challenge (SC2) – SCATTER approach

DARPA SC2 is aimed at dynamically sharing spectrum, without the need for knowing which network technologies are using the spectrum specific. It should provide a system of cooperative sharing, which offers fairness and coexistence in any possible spectrum range. There is no longer be a distinction between licensed and unlicensed spectrum.

SC2 assumes that a *low-rate communication channel* exists between all spectrum users to support collaboration. The channel is used to exchange simple performance, observation, and request information. *AI techniques* and *advanced optimisation techniques* allow the network of radios to robustly optimise for any desired ensemble state.

The SCATTER method (IMEC and Rutgers University), a challenge winner, is SDR and AI-based and offers:

- Very fine-grained (transmission slot level) sharing, leading to high sharing efficiency.
- Active/passive incumbent protection
- Spatial reuse of frequency/time slots
- Decentralised operation: All decisions for dynamic spectrum allocation and usage are taken locally at each node.
- Spectrum usage prediction: SCATTER, can, using AI, predict and react proactively to future spectrum usage events.

The SC2 concept has been experimentally proven, but it is radically different from the state-of-the-art of spectrum allocation and sharing concepts, and, if adopted, would have impact on the present business models of MNOs, and new verticals. Hence, we consider it as a beyond 5G method.

- **Authorisation regime** : unlicensed
- **Frequencies:** various sub 6 GHz bands used in testbed emulations.
- **User hierarchies**: no hierarchy, equal opportunities for Wi-Fi, LAA and 5G NR-U cellular users.
- **Radio technologies:** radio-technology agnostic.
- **Spectrum access policy:** local access decision based on AI prediction and exchange of information through a control channel.
- **Spectrum usage status acquisition method:** sensing and control channel for status dissemination.
- **Spectrum-sensing metrics:** Radio technology and behaviour detection for prediction.
- **Status:** research concept and testbed experience.

Advanced Radar and Communication Spectrum Sharing

The concept is developed to allow communication networks that use OFDM (e.g., 4G, 5G and IEEE 802.11) and BS beamforming to share spectrum with advanced phased-array pulse radar operating in the S band (2-4 GHz). The radar system is the Primary User (PU), while the communication network is a Secondary User (SU), that should operate in an underlay sharing mode. This is different from the sharing in white-space mode, where communication systems consult a geo-database to check whether in a particular geographical area and in a particular time period the radar is operational and should not be disturbed, e.g., as in TVWS and CBRS. The control over how spectrum is accessed by the SUs, is done by the BS. This is done by optimising the beamforming and signal power control, to keep the interference level at the radar below the limit and the SINR (signal-to-noise-and-interference ratio) sufficiently high. There are no implementations yet of this concept, only simulation studies. It is an example of how BSs with hybrid or digital beamforming can use complex signal-processing to reduce interference with incumbents and have much better opportunities for sharing spectrum.

- **Authorisation regime:** unlicensed and licensed
- **Frequencies:** studied for S-band (2-4 GHz) operation
- **User hierarchies**: two-tier: incumbent radar stations and MNOs.
- **Radio technologies:** cellular LTE or 5G NR and Wi-Fi.
- **Spectrum access policy:** concurrent spectrum access (underlay) coordination.
- **Spectrum usage status acquisition method:** space-based detection: Direction-of-Arrival (DoA) estimation.
- **Spectrum-sensing metrics**: signal strength and DoA.
- **Status:** research concept and simulations.

Annex G Some advanced technologies to support DSS

Spatial spectrum sharing

Massive MIMO in 5G, in the sub 6 GHz domain, is characterised by the fact that the BSs are equipped with an antenna array with a large number of antennas (e.g., 256), much larger than the number of UEs served simultaneously. UEs still use one or a small number of antennas simultaneously. All elements of the BS antenna array serve the multiple spatially separated users in the same time-frequency resource. The multiple RF chains at the BS allow spatial multiplexing and hence also sharing of spectrum between different networks, either having their own infrastructure (BSs) or a shared infrastructure, as long as the interference of "beams" serving a UE belonging to one network with the receivers of another network stay below a maximum tolerance threshold.

In the mmWave domain beamforming is mandatory, to compensate for the significantly higher pathloss in these frequencies, e.g., the IEEE 802.11ad standard supports up to four transmitter antennas, four receiver antennas, and 128 sectors (beams). Both transmitter-side and receiver-side beamforming are supported. mmWave beamforming is also part of 5G-NR.

In mm-wave systems using transmit-side and receive-side beamforming, and ultra-narrow beamforming spatial spectrum re-use could be pushed very far. This would require very large antenna arrays, which become feasible in the mmWave domain, because the size of the antennas and their mutual distance is of the order of the wavelength.

Consequently, beams provide a new dimension for sharing of spectrum for multiple access technologies. However, spatial spectrum sharing is still to a large extent a research topic.

AI Techniques: Machine Learning (ML)

A lot of research is going on the application of AI to wireless communication and to dynamic spectrum management (DSM) in particular. Machine Learning (ML), based on deep learning, has turned out to be a powerful tool to perform system functions that otherwise would be too difficult, too computationally complex or not scalable. Deep learning combines advances in computing power, in particular based on GPU processors and special types of deep neural networks, i.e., neural networks with more than three layers, to learn complicated patterns in large amounts of data.

Research on ML techniques for DSM has mainly been used for:

- spectrum sensing
- signal classification and traffic recognition
- spectrum-usage prediction
- dynamic spectrum access decisions.

AI based solutions, in particular ML neural networks, have a number of advantages with respect to classical algorithmic solutions:

- Often, they do not require domain knowledge, e.g., in determining what wireless technologies are present from sensing the IQ-signal samples.
- They are computationally less complex and hence faster and more energy-efficient than classical solutions. This implies that certain functions can be performed in real-time that previously could not.
- They are often more robust (i.e., still work) when the operational circumstances deviate from what an original design was assuming.

The drawbacks are:

- The initial offline training, which is done before the system becomes operational, can be costly (lengthy), and appropriate training data must be generated through simulations or measurement campaigns. Some of the problem can sometimes be alleviated by an online-learning neural network.
- The design of ML-based solutions requires skills and experience, e.g., to design an effective neural network architecture suited for the task at hand. There seems to not yet be a design theory, which would allow to synthesise a particular neural network based on a set of requirements. The design choices made in research papers, often rely on prior experience with similar problems.

Implementing ML-based solutions becomes attractive because the availability of special GPU-based processor chips intended for executing AI tasks, is growing fast, resulting in faster execution times and less energy consumption. Moreover, new generations of CPUs, will often contain, next to multiple classical Von Neumann-style cores, also GPU-style cores, e.g., to implement neural networks.

While in several documents we found with desk research "Artificial Intelligence" was mentioned as a promising possibility or future element, we didn't find concrete examples in the regulatory & industry realm, outside of AI used to deal with / interpret sensing measurements.

Full-duplex (FD) Radio

The use of full-duplex radios, i.e., radios that are able to transmit and receive on the same channel concurrently, are, in principle, a powerful means to improve the efficiency of spectrum sharing. If we consider the case of sharing between PUs and SUs, the SU could be informed of the transmission status of the other nodes, by spectrum sensing, while it is transmitting on the same channel. With present SU radios sensing and transmitting is in half-duplex mode, e.g., using the LBT access method.

An example scenario where this could be of benefit is an underlay spectrum sharing system, where unlicensed SUs are allowed to operate within the service range of licensed PUs, as long as the level of interference from SUs to PUs is below a threshold (at the PU receivers) that guarantees that the QoS requirements of the PUs are met.

Data transmission with half-duplex SU radios, can only utilise the part of each slot (in a slotted system) after sensing. With FD radios, transmission can go on continuously as long as no PU activity is sensed.

However, there are still some issues with full-duplex radio, e.g., the higher energy consumption due to the signal-processing required for cancelling the self-interference.

In order to exploit the potential of full-duplex radio, in particular for spectrum sharing, a lot of research is still needed. On the other hand, IEEE 802.11 is considering FD radio for their future IEEE 802.11be (Wi-Fi 7), extremely high throughput standard, and experimental research is taking place.

Radio Virtualisation and Infrastructure Sharing

Network virtualisation and network slicing for sharing of network infrastructure among different virtual networks and offering, e.g., different QoS., are part of the 5G portfolio of all major telecommunications manufacturers. Sharing of the radio heads (in BSs and APs) however, has not reached this stage yet, it is a subject in 3GPP. It has great potential to drive down infrastructure cost and causes new business models for MNOs. It is also a technology that supports very efficient dynamic spectrum sharing, e.g., for allowing an MNO to provide spectrum as a service in eLSA to a vertical operator.

For example, one could allow a number of independent wireless networks using the same hardware (BS or AP) to operate, in parallel and isolated from each other, sharing the same spectrum in a dynamic way. This could be done with networks that use OFDM-based transmission, which is the case in, e.g., Wi-Fi, NB-IoT, LTE and 5G NR.

An infrastructure provider could, for example, split its owned spectrum band into smaller chunks and lease it to verticals. Another possible example is for an operator, instead of splitting its own spectrum into smaller chunks, to provide other operators access to their own spectrum bands.

It is a proven concept that has been prototyped and demonstrated successfully in the DARPA Spectrum Challenge. We expect that, given the pressure to significantly improve spectrum utilisation through dynamic sharing and the need to drive down infrastructure costs resulting from network densification, radio virtualisation will play a significant role in the future.

Blockchain Technology

The main idea behind blockchain is to distribute the validation authority of the transactions to a community of nodes and to use cryptographic techniques to guarantee the immutability of the transactions. According to the FCC, blockchain could be used to reduce the administrative expenses of dynamic spectrum access systems and thus increase the spectrum efficiency. A lot of research is going on in exploring the benefits of using blockchain technology to spectrum sharing.

Another example is blockchain-enabled cooperative dynamic spectrum access, in which the technology is used to protect the cooperative sensing by multiple SUs against malicious SUs, in a distributed way, such that it is also protected against a possible attack on the sensing fusion centre.

The application of blockchain technology to dynamic spectrum access is still very much a re-search topic, however experimentation with blockchain is already happening.

Eric Fournier, from ANFR (France), stated in the DSA-conference (November 2020) on 6 GHz Standard Power Access Points[24]:

> *To be harmonised in a second step?*
>
> - *Then, key question is geolocation/database in the European context*
> - *ANFR has developed a proof of concept based on blockchain*

While the ANFR director didn't elaborate much further in his statement it was indicated that ANFR was open to cooperation with other Radio Agencies to engage in tests with their blockchain Proof of Concept.

A French language press release describing ANFRs Proof of Concept with blockchain has been released[25]

Protocols and parameters for spectrum sharing

Most descriptions of Dynamic Spectrum Sharing systems, we found during our desk research in the industry and regulatory realm don't expand beyond high-level system architecture views.

Detailed documents with protocols and parameters are sparse. PAWS is referenced for TVWS and for the high frequencies it is now CBRS or a "slimmed down CBRS-protocol".

For PAWS using IETF RfC 7545, the protocol is made available at: https://tools.ietf.org/html/rfc7545 . In their parameter fields they declare either a set of FCC parameters (for the USA) or ETSI (for Europe). With respect to ETSI the reference is to ETSI EN 301 598 V1.1.1.

For the American CBRS-system the standards are listed at https://cbrs.wirelessinnovation.org/. The legal requirements for registration are described in the FCC rules.

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[24] http://dynamicspectrumalliance.org/wp-content/uploads/2020/11/5-Economic-and-Social-Impact-of-Unlicensed-Access-in-6-GHz-Band.pdf, see slide 16

[25] https://www.anfr.fr/en/anfr/politique-dinnovation/actualites/actualite/actualites/blockchain-pour-le-wifi-6-ghz-un-demonstrateur-de-gestion-innovante-de-partage-dynamique-du-spectre/

Specifically, 96.39(c):

(c) Registration with SAS. A CBSD must register with and be authorised by an SAS prior to its initial service transmission. The CBSD must provide the SAS upon its registration with its geographic location, antenna height above ground level (in meters), CBSD class (Category A/Category B), requested authorisation status (Priority Access or General Authorised Access), FCC identification number, call sign, user contact information, air interface technology, unique manufacturer's serial number, sensing capabilities (if supported), and additional information on its deployment profile required by §§96.43 and 96.45. If any of this information changes, the CBSD shall update the SAS within 60 seconds of such change, except as otherwise set forth in this section. All information provided by the CBSD to the SAS must be true, complete, correct, and made in good faith.

also FCC rules 96.45(d):

(d) When registering with an SAS, Category B CBSDs must transmit all information required under §96.39 plus the following additional information: antenna gain, beamwidth, azimuth, downtilt angle, and antenna height above ground level

It must be noted that in the US implementation of CBRS, Category A is limited to 30 dBm/10 MHz EIRP and is mainly allowed to be used indoors, and in limited outdoor situations. Category B is allowed 47 dBm/10 MHz EIRP and is only allowed outdoors.

Use of CBRS or a new system like AFC (for 6 GHz devices) will probably boil down to more or less the same protocols and parameters.

Most other documents reviewed are alas surprisingly thin on the spectrum management parameters required and the protocols used for information exchange. The 20 November 2020 article written by Fairspectrum on sharing between satellite and IMT is an exception. For that testbed they used a 'slimmed down' version of the signalling protocol used for CBRS device communications with the SAS.

CONTACT

Over Stratix

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