Stratix

Trends and options in efficient spectrum use

REPORT

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Management Summary

Radio spectrum is being used more and more extensively. Applications on smartphones and laptops with increasing volumes of transferred data are used more frequently by more users, leading to an increased demand for bandwidth in both commercial licensed spectrum for mobile communication such as LTE and license exempt spectrum for short range communication such as Wi-Fi.

Universities and research facilities face a challenge if demand for cheap, high quality wireless broadband connections on campuses keeps growing while the available radio spectrum stays limited.

Technological advancements in both LTE and Wi-Fi technology enable more efficient use of allocated spectrum by sending 'more bits/s per used Hertz', but there may be situations where these solutions still do not provide enough bandwidth or where they are too costly.

An important way to increase the available usable spectrum is 'sharing' of radio spectrum that is licensed for primary use to other parties, but that is not used at a given time and place. This is of course only feasible if this does not interfere with the primary application, regulation of such use is in place, equipment is available and there are clear advantages in terms of offered bandwidths, cost and flexibility.

Secondary use in itself is not a new phenomenon. Several frequency bands have been assigned for secondary use for, among others, radio amateurs, low power wireless microphones, and other short range devices. However, these assignments have been fairly static, while trends in technology now allow for more dynamic and therefore more effective forms of spectrum sharing.

Internationally, a number of initiatives for enabling the use of shared radio spectrum have been started, using geo-location databases in which spectrum use is registered in order to determine which frequencies can be 're-used', or using Cognitive Radio techniques in which sensing of other radio traffic helps determine which radio frequencies are available.

Mass introduction of such solutions still faces a number of challenges: equipment needs to be much more flexible with regard to the use of different radio bands, and protocols, and standards for geo-location database access and interworking of Cognitive Radio devices are not yet properly defined. Trends like Software Defined Radio may offer solutions for these challenges. Additionally, there are challenges in regulation and legislation, in order to enable secondary use within limits to avoid disadvantages for the primary users.

This report gives an overview of relevant initiatives and trends, both from technology and regulatory perspective.

1 Introduction

1.1 Background

Ever since the invention of radio communication, spectrum has become more and more crowded: the number of users grew, new applications were added such as voice communication and radio and television broadcast as well as military applications, all leading to increased demands on spectrum. More recently, the introduction of mobile phones (starting with primitive carphones in the 80's, but rapidly expanding with the introduction of cellphones as a commodity in the 90's, with currently up to 6 billion subscriptions worldwide[1]) has put a major pressure on spectrum availability.

Nowadays, with the explosive growth of (mobile) Internet and the expectation of wireless access to information whenever and wherever we want, demand has grown even further: people use computers and tablets with wireless connections; "phones" (this might no longer be an appropriate name) are often used more to browse the internet, to watch video, or to take pictures and upload them to Picasa then they are to "make calls" in the traditional sense. Video is watched in an "on-demand" way by many people, reducing the numbers of people that watch a television broadcast at the same time, while larger numbers of people watch that same program at some later time or date. Voice communication now requires only a very small amount of the available bandwidth in comparison with other uses, and has become only a minor application of spectrum (allbeit with specific quality requirements).

At the same time, technology advances have made it easier to set up and utilise small wireless networks, creating opportunities for "normal" people that where unthinkable 20 years ago, a time when even DECT in-house cordless phones had not yet been introduced.

While these trends all contribute to an increasingly crowded spectrum, this does not mean that the spectrum is used in the most possible effective way. In fact, large parts of the radio spectrum are unused at any given time and place. However, making use of this unused spectrum requires new rules and new products. This Report is a quickscan into the major trends in allowing for more efficient use of radio spectrum from the perspective of technology, use, market, standardisation and regulation.

1.2 Stakeholders

There are a number of different Stakeholder groups involved in the use of radio spectrum. Two possible categorizations of these stakeholders are by technology perspective, and by "spectrum-user" role:

By technological perspective:

- Active transmission, active reception: users of two-way radios, Wi-Fi, Bluetooth; users and providers of mobile telephony;

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[1] http://mobithinking.com/mobile-marketing-tools/latest-mobile-stats/a#subscribers

- Active transmission, 'passive' reception: radar operators (including large radar systems such as military or precipitation radars, but also car drivers using proximity radar);
- Reception only: TV and Radio broadcast consumers, but also Radio Astronomy, reception of time signals, remote controlled toys;
- Transmission only: TV and Radio broadcasters, but also time signal broadcasters and some types of telemetry users.

By business or "spectrum user" -role:

- Licensed public operators, for instance:
    - Mobile operators (Base stations for LTE, UMTS, GSM);
    - Broadcasters (T-DAB, DVB-T and FM transmitters);
- Unlicensed private network owners, for instance:
    - Residential users (Wi-Fi access points and DECT phones at home, Bluetooth in cars);
    - Commercial and institutional users (company networks, university or public building networks, for instance based on Wi-Fi);
    - Program Making and Special Events (PMSE) users (wireless microphones).
- Military, emergency services, and other official use, for instance:
    - Military radar
    - Aviation (radar, voice communication, telemetry)
    - Emergency services (voice and data communications)
    - Meteorology services (radar, probe telemetry)
- Astronomy projects, for instance:
    - e-VLBI, LOFAR
- End-users

Each categorization shows that there may be (very) different interests in radio spectrum from a different point of view: operators pay for exclusive use of parts of the spectrum, so they can build a (country-wide) network to build their business around, for which they want full control, minimized interference, and strict limitations on potential competitors or competing technology, while other stakeholders (like end-users) have different interests and may only want to use part of the spectrum in a limited area, for high-bandwidth but localized private use.

2 Radio spectrum policy and frequency usage

2.1 Current spectrum policy

2.1.1 Licensed Spectrum

For Licensed spectrum the authorities[2] provide a license to a party to use that spectrum under certain conditions. Current practice is that in most cases that party has the sole right to use that spectrum, allowing them to create a network based on that spectrum without interference from others. Examples are the licenses for spectrum in the 900MHz and 2.1GHz bands for mobile telecommunications (currently used for GSM and UMTS), in which commercial network operators such as Vodafone or T-Mobile create a patchwork of small cells to cover a large area or country.

Other examples of licensed spectrum are spectrum for Radio Broadcast (both analog and digital T-DAB), C2000 or DVB-T, each giving the licensee the rights to use part of the spectrum for certain goals. Some licenses give the owner the right to use the spectrum anywhere within a country; other licenses have a geographical restriction, like the Dutch 3.5 GHz license which may not be used in the northern part of the Netherlands (since it would interfere with satellite interception), or restrict usage to an exact location and direction such as a license for a microwave link. Most licenses have at least some form of restriction concerning interference into neighboring counties; for instance, for DVB-T there are international agreements which limit the use of certain parts of the spectrum to certain areas.

2.1.2 Unlicensed Spectrum

For use of unlicensed spectrum, no license is needed, but restrictions usually do still apply, often related to the maximum radiated power to reduce interference in order to allow many users to use the spectrum. In some cases, the specific protocol is regulated, while in others the restrictions are only on power and duty cycle[3].

There may also be administrative rules for the use of unlicensed spectrum; for instance, a private GSM system in the Netherlands in the unlicensed part of the 1800 MHz band has to be registered with the Dutch regulator (Agentschap Telecom). Similarly, radio amateurs do not require a license, but they do have to have a certificate of competence and they have to register their equipment with the Agentschap Telecom.

Unlicensed spectrum is currently assigned for various purposes and in various bands, such as:

- Wi-Fi, Bluetooth, Zigbee, and other protocols using the 2.4 GHz band;
- RFID;
- Private GSM in a part of the 1800 MHz band.

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[2] In the Netherlands, the responsible agency is Agentschap Telecom

[3] Duty cycle: the percentage of time, within a short period, that a device is actually transmitting.

Wi-Fi and Bluetooth

Two well-known examples of unlicensed spectrum are the “Wi-Fi bands”, which is the spectrum between 2.4 GHZ and 2.484 GHz (the 2.4GHz-Band) and the 5 GHz band. This spectrum can be used by everyone, under conditions of low power; the 2.4GHz band can be used for any application (with some restrictions) while the 5GHz band can only be used for “Radio LANs” (which in practice means Wi-Fi). Since there is only a limited number of independent Wi-Fi channels in each band, the ‘free’ use, combined with the large scale of use (households often have one Wi-Fi access-point each) often leads to interference in densely populated areas. In the 2.4GHz band, not only are there less channels but the band is also used for other applications (for example for Bluetooth, which is heavily used for short-distance communication for wireless keyboards, mouse, headsets etc.), leading to more interference.

Private GSM

A very different model for unlicensed use is “private GSM” in the 1800 MHz band. With the original allocation of spectrum for mobile operators in this band, two 3,5 MHz pieces of spectrum were barred from use in order to shield DECT phones from interference by GSM. When it became clear that DECT phones would not suffer from a low-power use of a part of that band, a general permission was given to use this spectrum without license.

Because this former ‘DECT Guard Band’ is part of the standardized spectrum for GSM and its successors, it is now possible to build low-power private GSM or private LTE networks in this band and use regular handsets on these networks without a license.

2.1.3 Unlicensed use in licensed bands

Even when a frequency band has been allocated for licensed use, it may be possible to allow for certain kinds of secondary use without risk of interference for the primary application. An example is the use of wireless microphones and audio feedback for Program Making and Special Events (PMSE) in the whitespaces in the bands reserved for DVB-T (TV digital broadcast). PMSE not only includes professional use in theaters and television production, but also semi-professional or amateur use of wireless microphones in churches, community centers and educational facilities.

2.2 Regulatory trends

In most countries in the world, governments are still making radio spectrum available for commercial use by exclusive licensing, often allocation licenses through auctions which generate income for governments[4]. However, there is growing awareness that the large societal and economic value of ubiquitous broadband access is of more importance than the income generated through these auctions.

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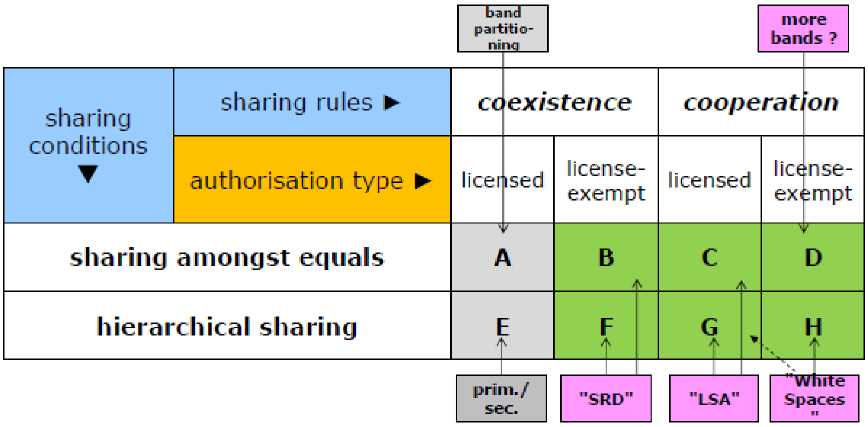
[4] The Dutch multi-band spectrum auction, which ended in December 2012, generated 3.8 billion Euros.

As Neelie Kroes stated[5]: "*The Digital Agenda can energise our economy, generate jobs, and save public money. But none of it can happen without fast broadband and quality digital services*".

2.2.1 Models for spectrum licensing

Several licensing models can be distinguished[6]:



sharing conditions ▼	sharing rules ▶	coexistence		cooperation	
	authorisation type ▶	licensed	license-exempt	licensed	license-exempt
sharing amongst equals		A	B	C	D
hierarchical sharing		E	F	G	H

Figure 1: licensing models

Current licensing models are mostly based on Licensing on 'equals' based for instance on the usage or protocols used:

- Licensed sharing amongst co-existing equals: Licenses are granted to spectrum users with the same type of usage, for instance DVB-T broadcasting by segmenting spectrum into licensed 'channels' (case A);
- License exempt sharing amongst equals: spectrum segments are allocated for some specific license exempt simple types of equipment (case B);
- Licensed sharing amongst cooperating equals: Amateur radio[7] (case C);
- License exempt sharing amongst cooperating equals: equipment is able to cooperate with each other to share the allocated spectrum such as Wi-Fi equipment (case D).

Hierarchical sharing aims at secondary or even tertiary use in 'white spaces' where the primary licensed user does not make use of the allocated frequencies: guard bands, or geographical locations that are located far away from radio cells using the same frequency band. In these situations secondary use may be possible when restrictions are applied with regard to, for instance, transmission power.

- The most basic form is hierarchical sharing of licensed coexisting users (case E): for instance by licensing radio spectrum in such a way that local radio stations can re-use the same frequency of larger radio stations in another part of the country.

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[5] http://blogs.ec.europa.eu/neelie-kroes/cef-digital/

[6] http://www.ieee-dyspan.org/panels_31_4239831924.pdf

[7] Mobile phones 'share' the spectrum, but mobile operators do not

Other licensing models that support sharing, and that will become more important in the future are:

- Licensed Shared Access (LSA) with users that cooperate with each other to efficiently use the spectrum (case G);
- "White Spaces Approach", such as 'cognitive radio' (case H);
- Short range devices legislation: streamlining is necessary (now primarily case B but can in some cases be moved to case F);

Changes in regulation can take a long time: long license periods and the ongoing use of existing technology make rapid changes almost impossible, but there is an international trend towards regulation enabling different types of sharing, This might involve not only sharing of radio spectrum primarily used for television broadcast or commercial mobile communication, but also sharing of spectrum allocated to government users such as defense[8] and emergency services.

In the US, the FCC has made a significant move towards the "white spaces" approach, based on central geo-location databases. To date, the FCC has authorized several companies to maintain such databases[9], while several devices have been approved which provide "white spaces" communication using these databases[10].

2.2.2 Regulatory trends in the EC

The objectives of the current Radio Spectrum Policy Programme (RSPP) of the European Commission (EC) are:

- A more efficient use of radio spectrum. A first step to achieve this is to make an "inventory" of use, users and usage trends in the member states specifically, and in the EC in general.
- To allocate 1200MHz for wireless broadband by 2015.
- To optimize sustainability, energy efficiency and economy.
- To support applications for Public Protection and Disaster Relief.
- To explore the potential of shared use of spectrum.

The EC is carrying out a number of studies to support the goal to improve efficient use of spectrum. An inventory and review of current use of radio spectrum[11] has been produced; currently ongoing studies are:

- The analysis of technology trends, future needs and demand for spectrum,
- Assessment of socio-economic aspects of spectrum harmonisation regarding wireless microphones and cordless video-cameras (PMSE equipment) and
- The impact of traffic offloading and related technological trends on the demand for wireless broadband spectrum

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[8] http://www.fiercewireless.com/story/att-verizon-t-mobile-forge-pact-explore-spectrum-sharing-government/2013-01-31

[9] http://transition.fcc.gov/Daily_Releases/Daily_Business/2013/db0227/DA-13-297A1.pdf

[10] For instance: http://arstechnica.com/tech-policy/2011/12/fcc-green-lights-first-white-space-device/

[11] http://ec.europa.eu/information_society/policy/ecomm/radio_spectrum/_document_storage/studies/inventory_2012/cion_spectrum_inventory_final_report.pdf

A number of observations can be made on changes in the EC vision with regard to efficient use of radio spectrum:

1. Wireless Broadband policy is now regarded with the vision that it should be more 'technology neutral'; rather than prescribing a technology, member states are encouraged to license spectrum for wireless applications in general.
2. Spectrum regulation is "polluted" by historically grown specific allocations and uses, and is in many cases country specific.
3. Spectrum is considered a 'finite resource': because it is "always scarce". Nevertheless allocated spectrum is in many cases used sub-optimally: allocated spectrum is used efficiently only from the perspective of the allocated user, and there is no incentive to share the spectrum with other usage and/or users where that is theoretically possible.

Sharing spectrum bands can be part of a solution, but this comes at a cost: protocols have to be efficient to optimize for use in time and space and to provide for (or deal with) alternative use of the same frequencies. This creates different incentives for different users, and leads to what is sometime called the 'spectrum crunch' debate:

- Existing users of allocated spectrum, who do not have to deal with increasing bandwidth demands for their application, prefer the status quo, avoiding costs;
- Existing users of allocated spectrum, who face increasing bandwidth demand of their users, prefer re-allocation of spectrum, minimizing costs, and still maintaining and controlling quality of service of their networks;
- Users of non-allocated or shared spectrum prefer more possibilities for radio spectrum sharing. Although their network use is adapted to the 'best effort' capabilities of connections, more available radio spectrum may create more flexibility and can increase capacity and reliability of individual user connections.

The EC is moving towards regulating sharing spectrum based on 'use patterns', instead of based on 'guard bands'. This allows for a more flexible allocation of unused spectrum between different applications.

There is an increasing awareness of the sometimes paradoxical links between regulation and standardization, and technological progress and market innovation, all aiming to optimize efficient use of radio spectrum, but in practice sometimes historically connected in a way that may 'lock' innovation in a certain direction.

The European Commission is, by aiming to promote "*the shared use of radio spectrum resources in the internal market*"[12], launching a debate and proposing action lines working towards:

- Establishing a common understanding of economical, technical and regulatory aspects of spectrum sharing;
- Setting out a strategy to promote shared access to spectrum;

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[12] European Commission Communication of Sept 3rd 2012, "*Promoting the shared use of radio spectrum resources in the internal market*", http://ec.europa.eu/information_society/policy/ecomm/radio_spectrum/_document_storage/com/com-ssa.pdf

- Setting a clear signal to innovators, showing that the EU is moving towards an advanced regulatory environment for wireless innovations allowing sharing.

2.2.3 Regulatory trends in the Netherlands

Although Dutch government recently held auctions to allocate spectrum in the traditional model, leading to exclusive seventeen-year licenses for mobile operators, it is also working towards a new paradigm which focusses on facilitating more efficient use of radio spectrum.

Licensing is becoming more technology neutral and more flexible. For instance, spectrum licenses may now be resold in whole or in part (within limits), and there is no longer a roll-out obligation (only a service coverage obligation, which may be fulfilled through other means than building a network). There is also a growing awareness that spectrum licenses for primary users should also include possibilities for (future) secondary users.

While regulatory changes can take a long time, experiments are often possible within shorter timeframes. To enable experimentation and innovation, the Agentschap Telecom has the power to grant experimental licenses outside the regular allocation policies. These licenses are always temporary, the frequencies may not be used commercially, and the use of these frequencies may not cause interference for regular users[13].

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[13] http://www.agentschaptelecom.nl/binaries/content/assets/agentschaptelecom/Frequentiemanagement/uitvoeringsbeleid-experimenteervergunningen.pdf

3 Trends in Technology and Usage

Massive adoption of improved technology is achieved by a combination of technology development in hardware and software and widely used and well maintained standards that support these developments in the evolution of existing network use or that support new use. Radio Technology trends are described in chapter 3.1, while chapter 3.2 describes the evolutions in existing network technologies. In chapter **Fout! Verwijzingsbron niet gevonden.** some conclusions are drawn on trends in existing networks and standardization.

3.1 Developments in Radio Technology

Smaller and more energy efficient hardware, and smarter and faster firmware and software have led – and are still leading - to large improvements in efficiency and flexibility of radio frequency use.

3.1.1 Improved spectrum efficiency

Technology advancements have led to an improved spectrum efficiency through better coding techniques. For example, LTE can achieve up to 16 bits/s/Hz, while GSM only achieved 0.5 bits/s/Hz and UMTS/HSDPA could achieve up to 8 bits/s/Hz .

Also, much has been achieved in the area of frequency reuse, and single frequency networks and ‘soft’ handover have increased the way spectrum could be utilized by operators.

3.1.2 Software Defined Radio

In conventional radio technology, the way signals were processed and converted to useful information was determined by the hardware. Even in modern handsets, the ‘software’ needed to decode or encode a signal is embedded in hardware chips, mainly due to performance considerations.

Presently there is a trend that more and more of those functions will be or are being implemented using software on a reprogrammable device, allowing for a much more flexible device, capable of using different protocols. Devices (both clients and base station side) can switch functionality by upgrading software or switching to another software element, theoretically removing the need to “add another chip” to allow for a mobile phone to use, for instance, Wi-Fi next to LTE.

There are still some considerations to take into account: although the signal-processing module can be reused and reprogrammed (allowing for multiple protocols to be implemented), the radio part determines what bands a device can receive or send. Developments in wideband antenna and radio technology will integrate wide-band capabilities within one antenna and one radio-module (modern smartphones can already receive GSM, UMTS, LTE or Wi-Fi signals in the ranges from 700 MHz up to 2.6 GHz or even 5 GHZ).

An example of the way a flexible software defined radio can work is implemented at the University of Twente in a project called "Wide-band WebSDR"[14]. In the project they use a wideband antenna to pick-up radio-signals below 25 MHz, use an AD-converter and make that piece of spectrum available via internet. The (web-based) software can then transform the digitized radio-signal, depending on the modulation technique you choose and the frequency band you select in the program, to a more 'useful' form like sound in the case of audio-broadcast. See http://websdr.ewi.utwente.nl:8901 for the website including the java-based program.

Other examples include hardware manufacturers making more flexible, software based systems (mainly for testing purposes for now)[15].

3.1.3 Spread Spectrum

Spread Spectrum technology uses a wider range of spectrum by 'frequency hopping' or other technologies like 'direct sequencing'. By using different frequencies to carry information smaller than one bit interference is less harmful and lower transmission power may be sufficient.

3.1.4 Ultra Wide Band

An extreme case of Spread Spectrum is Ultra Wide Band (UWB). This technology uses of a very wide frequency band (much wider than conventional "wideband" systems) combined with a very low power density.

UWB allows for low range, high throughput data-communication, by sending pulses for a very short duration of time and at a low power to transmit a signal. UWB signals avoid interfering with other signals through a power level too low to be detected above the regular noise (although, like any other signal, it still contributes to that noise so that a large number of UWB devices could create a discernible elevation of the noise level).

3.2 Evolution or new use of existing network technologies

3.2.1 Developments in Wi-Fi

Since the first variant of Wi-Fi was developed in the early 1990's (in Nieuwegein, the Netherlands) and standardized as IEEE 802.11, a large number of extensions and improvement have been made, including the use of OFDM, single user and multi user MIMO (optimizing the use of multiple antennas per device and/or access point), and multiple simultaneous data streams.

Wi-Fi can be seen as a form as 'cognitive radio', meaning that it uses information from its environment to adapt its behavior: it uses the 'listen before you talk' concept, and is capable of dealing with unknown other users sharing overlapping frequency bands. The standard

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[14] http://websdr.ewi.utwente.nl:8901/

[15] For instance: http://www.radiotechnologysystems.com/sdr_basic_info.html

even has rules for sensing and avoiding interference with (weather) radar use (Dynamic Frequency Selection, part of the 802.11h standard).

The standard and the implementations are still evolving, enabling faster transmission rates, improved reliability and extended flexibility with regards to the radio spectrum that can be used.

In the near future (within a few years) transmission layer data rates of up to 6 Gbps (short range) are foreseen. Small cells and/or beam forming will be used for high density, high usage use cases, while lower frequency bands are used for lower density, longer range use. This combination will make Wi-Fi both future proof and backwards compatible.

3.2.2 Developments in Mobile Operator Networks

In the last 15 years mobile operators have implemented several solutions to deal with the challenge of maintaining nation-wide coverage of their networks, while coping with increasing user numbers and increasing usage (both in voice and also increasingly in data). Where initially the focus was on coverage (large cells for not too many users), the focus shifted to seamless service provisioning, building more cells to fill in the gaps and provide for seamless handover, and nowadays the main challenge is to provide enough capacity where it is needed. This is done by introducing smaller cell sizes (pico cells) and flexibility to introduce (temporarily, mobile) cells when and where needed.

Also, very small “femto” cells have been introduced which can be installed by end users themselves to optimize in-home or in-office connectivity. These femto cells are connected to the mobile network using an existing fixed line (Internet) connection.

Residential Wi-Fi, especially when opened to public use, poses a potential competitive threat to mobile operators, but on the other hand mobile operators are trying to find ways to ‘offload’ excessive data traffic from mobile networks (for instance by crowds of static ‘heavy’ users) by using Wi-Fi access as an alternative.

3.2.3 Developments in private use of LTE

Private GSM or private LTE networks have become a viable options for organizations: these systems are sometime offered by regular operators as an extension of their network, but creating your “own” GSM, UMTS or LTE cell is also possible. Network-elements for a limited number of users can easily fit in a small computer cabinet, and Ethernet based radios (pico or femtocells) are available for creating indoor or onsite coverage.

Running a private GSM network has the advantage, aside from possible cost benefits, that the user can create services directly on the infrastructure. For instance, a hospital could dispense with a separate paging system by implementing an “urgent” SMS feature using flash-SMS on the private network which is not usually provided by public networks.

Mobile operators are not always willing to cooperate with users of private GSM networks, as some see this as a threat to their market potential. However, in some cases they view this as a new chance and they cooperate, allowing for a single handset (and SIM) to roam between the private and public networks.

3.3 Trends in technology and standards

Although there are many different standards used to provide wireless data connectivity, three standard suites are used far more than any other. Each of these standard suites has a large custom base and supporting equipment, and each is still evolving with increasing spectral efficiency through newer variations of the standard:

- Bluetooth and Wireless USB for unlicensed, very short range data traffic;
- Wi-Fi for unlicensed short range data traffic;
- (3GPP) LTE for mobile operator administered medium and long range data traffic.

Standards are no longer 'tied' to specific radio layer protocols and specific frequency bands, but more and more often serve as protocol platforms that enable wireless devices to quickly negotiate, enable and optimally use the technology and radio frequency capabilities available in both devices.

IEEE 802.22 and 802.11af both address data communication through TV white spaces (sometimes called 'Super Wi-Fi'), but use different approaches. Aim of these standardization efforts is to use white spaces between channels currently used for television broadcast, to provide for Wi-Fi channels that can be used for longer range communication and/or communication less perceptive to signal blocking by infrastructure (walls etc.). 802.22 is focused on long distances (for instance for rural broadband) while 802.11af is aimed at shorter distances and higher bandwidths.

Technical developments described in 3.1 are already leading to more generalized and flexible components for radio transmission and reception, combined with the flexibility of "software defined radio" of client software in firmware. This leads to larger flexibility to adapt standards such as LTE for use in alternative radio frequency bands.

A more flexible use of spectrum also leads to a need for new standards for coordinating this sharing and to supporting handovers between different technologies and networks.

4 Mechanisms for more efficient spectrum usage

Section 3.1 mentioned several ways to achieve a "more efficient use" of spectrum. Of particular interest are combinations of these advances in technology and advances in regulation which make it possible to take a more flexible approach to spectrum licensing. These combinations are sometimes referred to as "cognitive radio", although the terminology is often used inconsistently.

There is no clear "one size fits all" solution to the problem of optimal spectrum utilization. To begin with, there is the "legacy use" of current spectrum which has to be taken into account. Also, there are different forms of spectrum use for different applications, and optimal utilization might differ per application. One-way broadcasting of a signal to a large number of possible receivers (as in radio or TV broadcast) is fundamentally different from multicasting a signal to a specific set of possible receivers or, more commonly, unicast connections to provide for the highly personalized, throughput of data we all expect from our connected devices (be it wired or wireless). Finally, there are different "Service Quality" requirements for different applications. Some applications just need short-distance or outdoor coverage, while others need long-distance or indoor coverage, some applications require that information is being transmitted "somewhere in the next 24 hours", while for others information may need to be dispatched immediately. For some real-time applications timely delivery of signals is more important than ultimate reliability, while for others reliability is of the utmost importance.

Priority of communication can also play a role: communication by some user groups, like emergency workers (police, fire brigade), is deemed more important than other forms of communication (certainly in case of an emergency or war). And in order to persuade those user groups to allow for any "shared use" of spectrum there must be mechanisms for them to exercise certain priority rights in case of an emergency.

Making more efficient use of spectrum is generally possible by using spectrum at times and locations where it is currently not being used, at power levels which don't interfere with its current use. Currently, there are two promising approaches to achieve this:

- Cognitive radio: devices which sense information about their environment, and adapt accordingly;
- Geo-location: devices which report their location to a central system, which informs them of the local conditions to which they must adapt.

Both approaches allow a device to adapt its behavior in order to operate at frequencies and power levels (and possibly other parameters) which allow it to function without causing harmful interference.

These two approaches are discussed further in the remainder of this chapter.

4.1 Cognitive Radio

There are a number of ideas generally grouped under the term "Cognitive Radio".

Those ideas include:

- Smart and dynamic network reconfiguration, based on the behavior of other devices;
- Dynamic sensing and then using of free spectrum (Listen before you send);
- Use of wide frequency bands

A common aspect of Cognitive Radio is that radio equipment can (semi)autonomously determine in what way communication can best be established under the circumstances.

There are multiple parameters that the equipment can sense and set in a cognitive and dynamic manner for optimal local communication settings, possibly including frequency and power, modulation techniques, protocols, and selection of spatial, directional or temporal free spaces.

4.1.1 Sensing of free or used spectrum

In order to “appoint” free spectrum in a dynamic way, sensing can be used to detect whether spectrum in a certain band is available. After finding a suitable piece of spectrum, the device can transmit on that band, (most likely) without disturbing other wireless communication sessions. There are two possible variants of this approach:

1. Protocol aware variant: the device is aware of the protocol used by the (potential) primary user(s) or usage(s) of the frequency band, and it can listen to protocol specific messages and use the derived knowledge. This approach is used by Wi-Fi to avoid interference with other Wi-Fi devices.
2. Protocol agnostic variant: the device is not aware of the protocol used by the (potential) primary user(s) or usage(s) of the frequency band; it simply detects that a device is transmitting power on a specific frequency and “knows” that it has to avoid that frequency. This approach is used by Wi-Fi to avoid causing interference for radars (particularly weather radar).

In the first variant the device can use the knowledge of the protocol to optimize the use of the band while minimizing the harmful interference with the primary users or usage. In the second variant such optimization is more difficult.

In either case, there is no guarantee that no harmful interference is caused for other applications, since detecting that no communication by other devices is taking place in a certain band does not mean there will be not be a communication at a later point in time. Therefore, next to finding a suitable band, continuous “collision detection‟ has to take place to detect interference. There are several possible responses when a collision is detected, also depending on whether the other transmitting device is also a secondary user or a primary user:

- A (random) timeout, similar to collision detection in wired Ethernet networks;
- A permanent or semi-permanent switch to another (potentially) free part of the radio spectrum;
- A device can switch continuously between several (potentially) free parts of the radio spectrum, temporarily or semi-permanently avoiding bands that are discovered ‘occupied’ (various variants of ‘frequency hopping’).

There are a number of challenges related to such “dynamic” allocation of spectrum based on client-side sensing and rules.

One challenge is that a set of rules need to be established to determine whether a piece of spectrum is free, meaning the residual signal in that band is of low enough amplitude so that a.) the residual signal is no problem for your communication, and b.) your communication causes no problem for the communication-session that the residual signal is a part of.

Two problems here are that “what is a low enough power or amplitude” might depend on what other kind of use you can expect to take place in that band, and what is a “low enough” residual amplitude on the sending end, might not be a low enough residual amplitude on the receiving end. Knowledge about what kind of usage is to expected in a certain band and a certain geographical location, for example using a centralized database, can help to streamline this process. When you know you are probing part of the TV-spectrum, you can use general knowledge about TV-broadcasts (like its transmitting-power, the minimal power required at the receiving end for the signal to be picked up by a TV, etc.) to determine what rules to use to determine whether a transmission may cause harmful interference.

Some smart Wi-Fi-access points work in a similar way: they dynamically probe the spectrum in the Wi-Fi-bands to determine what frequencies are occupied (i.e. the frequency used by your next-door neighbors access point), and then select the most appropriate channel to use for itself.

Another challenge is how to negotiate between two devices what frequency to use: preferably, the receiving device should know to what band it should listen to before the other device starts broadcasting. One way is to use predefined parts of the spectrum, which are known to be available, for coordination purposes. A different way is for the receiving device to scan an large part of spectrum, looking for a particular transmission. Wi-Fi uses both approaches: in general, a client device will scan all Wi-Fi channels in order to find an access point, but Wi-Fi devices can also coordinate a frequency change by doing a short exchange on the old channel when, for instance, a weather radar is detected within that channel.

An example of a pilot with dynamic Spectrum access is the Raytheon/DARPA WNaN-research-project[16]*, in which the aim is to pilot a system that automatically detects the best available frequencies to use for communication between multiple clients. Communication takes place using multiple frequency bands at the same time, creating resilience. If one frequency is disturbed, the entire ecosystem of clients will replace that band with another available frequency to ensure no calls are dropped.*

4.1.2 Dynamic sharing of a band

Another way to (re)use spectrum is to not only look at free parts of the spectrum, but to also detect free time slots (or even other aspects of wireless communication like polarization) within a band and utilize those.

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[16] http://bbn.com/news_and_events/press_releases/2012/pr_wnan_110512

A simple way is to tune to a specific frequency and to "listen before you send", and then to only start transmitting if no other usage is detected.

Of course more sophisticated detection and pattern recognition algorithms can be used to make use of empty "timeslots". Smart algorithms might be able to detect empty timeslots, and prior knowledge about what protocols there are (and what usage can likely be expected in that specific frequency range) will help in creating algorithms that are optimized for that task.

4.1.3 Smart and dynamic network reconfiguration

Smart network reconfiguration is a way to dynamically alter the effective coverage of a network by changing network-topology based on certain dynamic parameters such as bandwidth demand or number of clients in a certain cell, or by using beam forming to increase the reach or capacity in a certain direction ("directionality"). The idea is to redistribute clients or load in such a way that overall performance of a network can increase.

One can think of redirecting users in the periphery of a busy cell to a neighboring "less busy" cell. For example, by adjusting the power of transmitters cells can grow to better accommodate users that are just outside the "natural" size of a cell[17], in order to relieve a neighboring cell (for example because a larger-then-normal group of users is located there). The "busy" cell can, by reducing power, reduce its size, allowing for a number of users on its edges to be transferred to the neighboring "less busy" cell. To decide on such a dynamic change of power of a constellation of cells or to direct certain clients in the periphery of a cell to a neighboring cell requires "overall network information" and the capability to make such overall decisions. Using a dynamic network configuration can mean that although the *overall* throughput is increased, the performance for some users might actually decline. The exact "rules" that such a system would use are under investigation, and will greatly depend on what the exact goal would be and what parameters – and to what extend- can be adjusted dynamically.

Examples of pilot-projects where experiments with such dynamic reconfiguration are for example the "Core/cwc" initiative[18] in Finland at the Center for Wireless Communication, in which they have a pilot setup to use a "cognitive" algorithm to offload data to neighboring base-station in order to increase the overall performance of the network.

4.2 Accessible registration and administration of frequency use

A second approach to discovering frequencies which may be available at a given time and place is to maintain a central database within which all devices in a certain band must be registered.

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[17] This is similar to what network planners would do in a more static fashion: Create a network planning and adjust power to account for the "average" number of people in a location, and for the performance the network-owner wishes to give to its clients. The "natural" cell size would be the static size of a cell, but in this example dynamic control allows to accommodate for fluctuation in user-numbers or load

[18] Core/CWC: http://www.tekes.fi/imageserver/images/programmes/project_results/10460038_en_1.pdf

4.2.1 Re-use of TV Whitespaces using geo-location databases

There is a significant amount of ‘white space’ radio spectrum in the TV and radio bands[19] (for example the DVB-T bands) used to broadcast radio and TV for large areas.

DVB-T uses spectrum from 470 MHz to 790 MHz, divided in channels of 8MHz. Different allotments are assigned for different regions, and conditions are set to prevent overlap between neighboring DVB-“cells”. In the neighboring area, that specific spectrum is “unused” for DVB-T (since that area is kept free to prevent interference), and can – under certain conditions – be assumed to be “white spaces”, and therefore the TV-spectrum is an often cited candidate for “secondary” use of spectrum. The main condition is the transmitted power; since DVB-T cells are in the order of tens of kilometers (with typical transmitting-powers in the order of tens of kilowatts), a condition for use in the “neighboring area” is that the effective radius and power of the secondary transmitters must be (much) smaller than the radius of the primary transmitter , or $R_{secondary} << R_{dvbcell}$ and $P_{secondary} << P_{dvbcell}$.

As the location, power and antenna pattern of the DVB-T transmitters is known, it is possible to maintain a central database which provides information on the locations, frequencies and conditions for secondary use. By registering the secondary users as well (temporarily, as these can be very dynamic users), interference between secondary users can be avoided as well.

Wilmington in the United States is the first city to use white spaces between television channels, not only as a pilot but also as a commercial service. The service is used for monitoring real-time water quality and traffic conditions in areas which did not have access to wired broadband connections.[20]

Another example of a pilot in which TV Whitespaces are locally reused is an initiative by the Singapore White Spaces Pilot Group[21] *which plans to conduct a number of pilots to use TV whitespaces to provide a WiFi-like (but more long-distance) service in and around the Singapore Harbour and shipping lanes and on a local Golf club. Part of the pilot makes use of a geo-location database which contains information about the availability of free spectrum and devices that probe the database to determine what spectrum to use at a given location.*

4.3 Status of shared spectrum technologies

Emerging technologies that support more efficient use of radio are in different stages of maturity. Generally, cost efficient large scale deployment of new technologies is only possible after passing a certain amount of development cycles. A well-known pitfall is investing in technologies that are promising, but not yet mature. Gartner describes this effect in the ‘hype cycle’.

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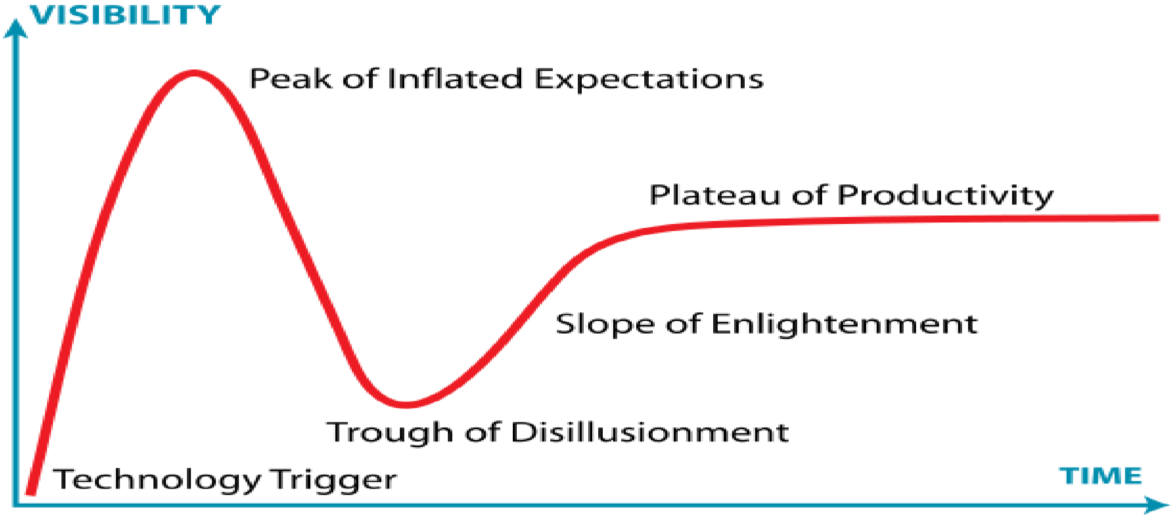
[19] http://www.inets.rwth-aachen.de/fileadmin/templates/images/PublicationPdfs/2011/DySPAN2011-TV-White-Spaces.pdf

[20] http://broadband.about.com/od/whitespace/a/Will-White-Spaces-For-Broadband-Work-For-Rural-Areas.htm

[21] Singapore White Space Pilot Group: http://whitespace.i2r.a-star.edu.sg/

The table below provides an overview of a number of technical developments and standards, directly or indirectly relevant to shared spectrum use, and their current place on the hype cycle according to Gartner.



Technology Trigger	**Peak of Inflated Expectations**	**Trough of Disillussionment**	**Slope of Enlightenment**	**Plateau of Productivity**
Cognitive Radio 802.11ah Smart Antennas for Cellular Applications LTE-A Optimized Download Network Virtualization WiMAX 802.16m	802.11u Cellular to Wi-Fi Authentication Cloud-Based RAN Mobile Self-Organizing Networks Tunable Frequency RF Antenna	Software-Defined Radio 802.22 802.11af Mobile WLAN access points	Femtocells Long Term Evolution 802.15.4/ZigBee 802.11k-2008 802.11n 802.11r-2008 Mobile Device Management Network Performance Monitoring Tools	802.3at

Table 1: Hype Cycle (source: Gartner 2012)

Shared secondary use of licensed spectrum is a topic with promising possibilities, but only a few real life implementations have been done so far. The real-life Proof of Concepts – for instance in a rural area in the UK – show that there are a number of elements specifically related to the local situation: spectrum use, equipment used by the primary users, licensing, user density etc. may lead to different outcomes in different countries and even within different countries. In the Netherlands, an active research community is present, the "Cognitive Radio platform"[22], and work is done at several universities related to legislation, regulation, and technical challenges in Cognitive Radio and Software Defined Radio, but no

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[22] http://www.crplatform.nl

real life pilot or proof of concept has yet been organized suited to the particular Dutch situation.

Both the Cognitive Radio approach and the Geo-location approach have been demonstrated in lab conditions and in live pilots. An overview of recent pilots and research projects can be found in Annex A. Especially because ‘sharing’ spectrum in most cases involves equipment from different vendors that has to interoperate, also the maturity of protocols and standards is important. An overview of relevant standards and protocols is given in Annex B.

Particularly interesting international projects and pilots are the Cambridge TV White Spaces Trial and the FP7 CREW project.

The Cambridge White Spaces Consortium in 2011 and 2012 carried out a proof of concept for shared secondary use of TV white spaces for rural broadband connections and machine-to-machine applications using a central (geo)database[23]. The British regulator Ofcom is using the results of this pilot to improve regulation for this type of applications, and to refine the standards for communication with the geo-database.

The FP7 CREW project (2010-2015) federates test beds at 5 different European locations. The CREW federated platform will support a benchmarking framework, enabling experiments under controlled/reproducible test conditions, allowing a fair comparison between different cognitive radio & cognitive networking concepts for different usage scenarios. Research is done on effects of sensing functionality, sharing in heterogeneous networks with densely population of various (Wi-Fi, Bluetooth, Zigbee, etc) devices, cooperation in heterogeneous networks in licensed bands, robust cognitive sensing networks and impact of cognitive networking in primary cellular (LTE) Systems.

Also it will be worthwhile to keep track of the not yet started Singapore White Spaces Pilot mentioned in 4.2.1, and initiatives in Kenya[24] and South Africa[25].

Aside from the cognitive aspects of existing equipment (particularly Wi-Fi), the geo-location approach is at this time further advanced than the cognitive approach. There are initiatives for several large-scale pilots, however all finished and ongoing pilots and deployments have used equipment which is not yet suitable for mass roll-outs. As the standards are not yet fully mature, there is no mass production; the equipment which is available tends to be produced in series of tens or hundreds, rather than the millions produced for Wi-Fi, GSM/UMTS and Bluetooth. As a consequence, the client device still costs four thousand Euros or more – a price level which may be acceptable in situations where there is no alternative, but which is not attractive for general purpose roll-outs.

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[23] http://www.cambridgewireless.co.uk/docs/Cambridge%20White%20Spaces%20Trial%20-%20technical%20findings-with%20higher%20res%20pics.pdf

[24] http://www.zdnet.com/microsoft-eyes-white-spaces-to-bring-broadband-to-rural-kenya-7000010897/

[25] http://www.techcentral.co.za/inside-sas-white-spaces-broadband-trial/37383/

5 Conclusions

Technologies which allow for a more efficient use of radio spectrum, including geo-location databases and cognitive radio, look promising for the future but are not yet ready for mass introduction.

Mass introduction faces a number of challenges: equipment needs to be much more flexible with regard to the use of different radio bands and protocols, and standards for geo-location database access and interworking of Cognitive Radio devices are not yet properly defined. However, the pilots that are currently happening in several countries are demonstrating that the approach does work, and the equipment is expected to improve quickly over the next few years.

The regulatory environment is also not yet ready. However, there are relevant developments in the UK and in the US which already provide more flexibility. Other countries are expected to follow.

Given these trends, it is to be expected that the coming years will provide significant opportunities for large scale users and for alternative operators to develop new radio networks based on the development described in this report.

Annex A Research projects and pilots

The following table provides an overview of research projects, technical developments and pilots related to use of white spaces in radio spectrum, cognitive radio and software defined radio.

Pilots and projects

Name	Context	Status	What			Description	website
			WS	CR	SDR		
Wilmington White Space Pilot	Pilot	Ongoing	x			world's first commercial white space network. first to use the frequency that once broadcast analog television signals to pilot next-generation programs.	http://wilmingtonbiz.com/industry_news_details.php?id=3257
Cambridge Whitespaces Consortium / Trial	Pilot	finished	x			Explored potential of television white spaces for other use. Explored and measured a range of applications — rural wireless broadband, urban pop-up coverage and the emerging "machine-to-machine" communication.	http://www.microsoft.com/presspass/emea/presscentre/pressreleases/April2012/24-04CambridgeTVWhiteSpacesConsortium.mspx
Singapore White Space Pilot Group	Pilot	in preparation	x			Super-WiFi in tv whitespaces	http://whitespace.i2r.a-star.edu.sg/
Core/CWC	Lab/PoC			x		Pilot setup to use a "cognitive" algorithm to offload data to neighboring base-station in order to increase the overall performance of the network.	
Raytheon/DARPA WNaN-research-project	Lab/PoC		x	x		Pilot a system that automatically detects the best available frequencies to use for communication between multiple clients	http://bbn.com/news_and_events/press_releases/2012/pr_wnan_110512
Wide-band WebSDR	PoC				x	Demonstration of SDR in which a The (web-based) software transformsa wide-band digitized radio-signal, depending on the chosen modulation technique and frequency	http://websdr.ewi.utwente.nl:8901/

Advanced Wireless Access Network Program (RASFA)/Brazil	Pilot			X		Cognitive Mesh Network, cognitive network architecture concepts	
Kenya TV white spaces trial	Pilot	planned	x			Uses TV white spaces to bring broadband services to underserved communities in Kenya	http://www.zdnet.com/microsoft-eyes-white-spaces-to-bring-broadband-to-rural-kenya-7000010897/
Twente/ Reconfigurable Platform for Cognitive Radio	Research	ongoing		X		Design and propose a cognitive radio platform	
CORNET / Virginia Tech	Research	Research network		X	X	CORnet is an operational network with reprogrammable elements for the purposed of performing advanced Cognitive Radio Network research	http://www.cornet.wireless.vt.edu/trac/wiki
Microsoft Specnet	Product Research			X			http://research.microsoft.com/apps/pubs/default.aspx?id=142837
PMSE	Product Research		X	X		PMSE equipment using sensing to provide continuous uninterrupted service	http://www.crplatform.nl/Documentation/Docs/12/Axient_ERx%20%5BRead-Only%5D.pdf
Open Spectrum	Awareness/pressure	grassroot initiative	X	X	X	Unlock the potential benefits of bandwidth for all using 'smart' radio techniques	http://www.openspectrum.eu
Nokia Siemens Networks on Spectrum Demand	Product Research	company research	x	x	x	Nokia Siemens Network research on Authorised Shared Access (ASA)	
The Cape Town TV White Spaces Trial	Pilot	planned	x			Create wireless dataservice based on tv whitespaces. Start 2013	http://www.tenet.ac.za/about-us/the-cape-town-tv-white-spaces-trial

Huawei Private LTE	Product Research					Provide equipment for private LTE networks in bands that are currently unused (or at least not used by ITU-LTE	
Tekes' Trial Environment for Cognitive Radio and Network programme	Research		x	x	x	Program in Finland that aims at stimulating pilots and research in the field of cognitive radio	http://www.tekes.fi/programmes/Trial/Projects
Nokia Research Center	Product Research		x	x	x	Nokia research	http://research.nokia.com/cognitive_radio
COGRadio (University of Colorado e.a.)	Research & Development	Research & development		x	x	Project is to develop a set of ruggedized, expandable and configurable multiradio cognitive radio systems that will facilitate experimentation by GENI researchers who have only limited experience with hardware development tools	http://groups.geni.net/geni/wiki/COGRADIO
FP7 Farimir	Research	EC 7th Framework Program		X		Aimed at moving the state-of-the-art cognitive radio technologies from concepts to factual engineering.	http://www.ict-faramir.eu
FP7 QosMOS (BT, ALU, NEC, Frauenhofer, Telenor, Thales etc.)	Research, test bed development	EC 7th Framework Program Integrating Project from call 4		x	x	Quality of Service and MObility driven cognitive radio Systems, develop a framework for Cognitive Radio systems and to develop and prove critical technologies using a test-bed.	http://www.ict-qosmos.eu/
FP7 COGEU	Research & Proof of Concept	EC 7th Framework Program	x			Cognitive radio systems for efficient sharing of TV white spaces in EUropean context. Introduction and promotion of real-time secondary spectrum trading and the creation of new spectrum commons in the upper band of the cleared spectrum.	http://www.ict-cogeu.eu/

FP7 CROWN	Research	EC 7th Framework Program		x	Cognitive radio oriented wireless networks. Dynamic spectrum licensing, distributed intelligence, cognitive radio, experimental platform	http://www.fp7-crown.eu/
FP7 CREW	Research & Proof of Concepts	EC 7th Framework Program	x	x	Cognitive Radio Experimentation World: incorporates 4 individual wireless testbeds (heterogeneous ISM @ IBBT-Gent, heterogeneous licensed @ TCD-Dublin, cellular @ TUD-Dresden, wireless sensor @ TUB-Berlin) augmented with SoA cognitive sensing platforms from IMEC (Belgium) and TCF (France).	http://www.crew-project.eu/
FP7 QUASAR	Research	EC 7th Framework Program	x	x	Assessing and quantifying the "real-world" benefits of secondary (opportunistic) access to primary (licensed) spectrum. The analysis is based on two key features of cognitive radio: the ability of the secondary users to discover the opportunity to use the spectrum, and assessing the electromagnetic impact of secondary user transmissions on primary system (receivers).	http://www.quasarspectrum.eu/
FCC initiatives for 'sharing' spectrum	Spectrum Policy	planned	x		The Federal Communications Commission and three major mobile operators in the US seek to investigate sharing of spectrum that until now was used for government use.	http://maps.yankeegroup.com/ygapp/content/1564ae97fa3a4ebb800b4a531040eaef/68/DAILYINSIGHT/0 http://arstechnica.com/business/2012/09/fcc-to-make-spectrum-sharing-reality-whether-carriers-want-it-or-not

FCC initiatives for 'white space' databases	Spectrum Policy	adopted	x		The Commission has adopted rules to allow unlicensed radio transmitters to operate in the broadcast television spectrum when that spectrum in not used by a licensed service.	http://www.fcc.gov/encyclopedia/white-space-database-administration
					The FCC Office of Engineering and Technology (OET) and Wireless Telecommunications Bureau Dec. 6 announced the nationwide launch of the agency's registration system for unlicensed wireless microphones.	http://transition.fcc.gov/Daily_Releases/Daily_Business/2012/db1206/DA-12-1956A1.pdf
Google enters FCC trial white space database	Spectrum Policy and white space Geodatabases	planned	x		Google enters FCC trial to test white space database designed to promote spectrum sharing	http://www.theverge.com/2013/3/4/4063166/google-enters-fcc-trial-to-test-white-space-spectrum-database
Kenya TV white spaces trial	Pilot	planned	x		Uses TV white spaces to bring broadband services to underserved communities in Kenya	http://www.zdnet.com/microsoft-eyes-white-spaces-to-bring-broadband-to-rural-kenya-7000010897/
DARPA program to develop technologies enabling radars and communications networks to share spectrum	Research Program	planned	x	x	The program seeks to support two types of spectrum sharing: Military radars sharing spectrum with military communications networks, and military radars sharing spectrum with commercial communications networks.	http://www.darpa.mil/NewsEvents/Releases/2013/02/08a.aspx

Annex B Standards and protocols

The following table provides an overview of protocols and standards related to use of white spaces in radio spectrum, cognitive radio and software defined radio.

Protocols & Standards

Naam	**Goal**	**Status**	**What**			**Description**	**website**
			WS	**CR**	**SDR**		
IEEE 802.22	Standardization	Implementation in pilot	x			Standardization effort is the use of lower frequency white spaces between channels currently used for television broadcast. Sometimes called 'Super Wi-Fi'. Developed in combination with 802.11af.	http://www.ieee802.org/22/
IEEE 1900 - DySPAN	Standardization		x	x	x	Dynamic spectrum access radio systems and networks with the focus on improved use of spectrum	http://www.dyspan-sc.org/
ECMA-392	Standardization		x			Specifies a medium access control (MAC) sub-layer and a physical (PHY) layer for personal/portable cognitive wireless networks operating in TV bands.	http://www.ecma-international.org/publications/standards/Ecma-392.htm
ETSI TC RRS	Standardization	Requirements		x	x	Generic concept based on technologies such as Software Defined Radio (SDR) and Cognitive Radio (CR) whose systems exploit the capabilities of reconfigurable radio and networks for self-adaptation to a dynamically-changing environment with the aim of improving supply chain, equipment and spectrum utilization.	http://www.etsi.org/technologies-clusters/technologies/radio/reconfigurable-radio
IEEE 802.11 (b, a, g, n)	Standardization	In force and in use		x		Current Wi-Fi standards suite (up to 4 streams and added 40 MHz channels in 5 GHz band in n-variant, up to 6.5 - 600 Mbps)	http://www.ieee802.org/11/
IEEE 802.11ac	Standardization	under development				More spatial streams, MIMO, 6.5 - 6933 Mbps	-
IEEE 802.11ah	Standardization	under development				Below 1 GHz. OFDM, MIMO, 150kbps to 86 Mbps, targeted for low power sensors	-

IEEE 802.11af	Standardization	under development		Below 1 GHz. Downclocked 11ac 40 MHz mode in TV white space channels for 6, 7, 8 MHz, Data rates from 800 kbps to 106 Mbps	-
IEEE 802.11ad	Standardization	under development		60 GHz band single carrier and OFDM, 27Mbps - 6756 Mbps, low range only, sensitive to signal blockage	-
Weightless	Standardization (Special Interest Group)		x	Weightless protocol (license-free white space M2M protocol)	www.weightless.org
ETSI EN 301 598	Standardization	near publication	x	Harmonized standard for Wireless Access Systems (Fixed, Mobile and Nomadic) in the TV Broadcast White Spaces in the 470 MHz to 790 MHz frequency band.	
Offcom - JFMG	Regulation/ standardization	in force (link not always reachable from NL)		JFMG Radio Spectrum for Program Making and Entertainment, met frequency database	http://www.jfmg.co.uk/
Ofcom VNS 2188	Regulation/ standardization	In force		Voluntary National Specification 2188 White space devices operating in the 470 MHz to 790 MHz band	http://stakeholders.ofcom.org.uk/binaries/consultations/whitespaces/annexes/draft-VNS.pdf
ietf PAWS	Standardization	development in progress		ietf work on Protocol to Access White Space database	https://www.ietf.org/mailman/listinfo/paws
IEEE 802.16h-2010	Standardization			802.16h-2010 - IEEE Standard for Local and metropolitan area networks Part 16: Air Interface for Broadband Wireless Access Systems Amendment 2: Improved Coexistence Mechanisms for License-Exempt Operation	http://spectralholes.blogspot.nl/2010/09/ieee-80216h-cognitive-wimax.html

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