Urban planning for Radio Communications

SP 1

Generic architecture of resource management and related protocols

Task 1.3

Spectrum occupancy: State of the art

Délivrable 1.3.1

Edition 11 29/01/2008

Editions

Edition	Date	Authors	Comments
ed. 0	17/07/07	M. Coupechoux, Ph. Godlewski, Ph. Martins (ENST)	Initial version.
ed. 1	11/09/07	M. Coupechoux, Ph. Godlewski, Ph. Martins (ENST)	Classification.
ed. 2	14/09/07	M. Coupechoux, Ph. Godlewski, Ph. Martins (ENST)	Research Projects DARPA XG, DRIVE/over DRIVE.
ed. 3	21/09/07	V. Capdevielle, N. Broqua, V. Kumar, ML Alberi Morel (Alcatel Lucent)	IEEE 802.22 summary State of the Art of existing systems
ed. 4	21/09/07	M. Coupechoux, Ph. Godlewski, Ph. Martins (ENST)	Research Projects E2R and WINNER. IEEE 802.16m.
ed. 5	24/09/07	M. Coupechoux, Ph. Godlewski, Ph. Martins (ENST)	IEEE 802.16d/e/h.
ed. 6	25/09/07	M. Coupechoux, Ph. Godlewski, Ph. Martins (ENST) + N. Broqua (Alcatel-Lucent) + J. Marzoni (SNCF)	Literature study + References and acronyms + existing systems.
ed. 7	15/10/07	C. Riou (Thales)	Regulation – P1900 – WAPECS / Sportviews
ed. 8	22/10/07	M. Coupechoux (ENST)	Final version
ed. 9/10	30/10/07	C. Riou (Thalès), M. Coupechoux (ENST)	Last corrections
ed. 11	29/01/08	M. Coupechoux (ENST)	Last corrections

Contents

1 Introduction

The aim of this document is to provide a state of the art in the field of radio spectrum allocation. The document go through the main methods for spectrum allocation in terrestrial mobile networks that take into account QoS considerations. Task 1.3.1 use the results of Tasks 1.1 and 1.2 to build a topology of the spectrum allocation methods. Task 1.3.1 focuses on the state of the art, while SP2 define new algorithms for spectrum management.

The document is organized as follows. The second part proposes a classification of the spectrum management models, mainly based on [1], and revisits the URC scenarios with respect to this classification.

The third part focuses on the state of the art. A first sub-part summarizes the main recent decisions of the regulator authorities in Europe (France, Germany, UK, etc) and United States (FCC) and at international level (ITU-R) concerning the spectrum management. A second sub-part focuses on the standards whose main concern is flexible radio or integrate the issues of flexible use of the spectrum in their specifications. The third sub-part summarizes the methods already foreseen in existing systems for spectrum management. Many research projects aimed at defining such algorithms in the past, the fourth sub-part lists the approaches proposed in these projects. At last, the fifth sub-part provides a state of the art of spectrum allocation algorithms in the scientific literature (conferences, journals).

The document is then concluded.

2 Spectrum Management Models Classification

2.1 Classification

In this section, a classification of the spectrum management models is proposed to be used throughout the URC project. This classification is mainly based on [1], the main characteristics of each of the classes are taken from [2]. Many such classifications exist in the literature [1-5][8-9] but few fulfill the desired features:

- Classes should be sufficiently different from a technical point of view. This means that the classification should be as independent as possible from regulation and economic aspects to not multiply the view angles.
- The number of classes should be sufficiently rich to take into account the various scenarios researchers have in mind. But the number of classes should be kept small for the sake of simplicity.
- Clear practical scenarios can be associated to each class and in particular URC scenarios.

The proposed classification is depicted on the following figure. There are four main classes :

1. **Command & Control**, which is the very basic case of spectrum management,
2. **Operator Sharing**: here, spectrum is owned by an operator. The use and ownership can be of long term or dynamic.
3. **Primary and Secondary Usage**: spectrum is basically used by a primary user, but a secondary user is allowed to access the spectrum in an opportunistic manner providing that the primary user is not disturbed. According to the PHY/MAC implemented by the secondary user, the share is said to be underlay or overlay.
4. **Commons:** spectrum can be accessed by several equal users. According to the amount of rules that can be applied by the regulator or a private owner of the spectrum, the Commons class can be further classified into Open Spectrum, Cooperative Commons and Private Commons sub-classes.

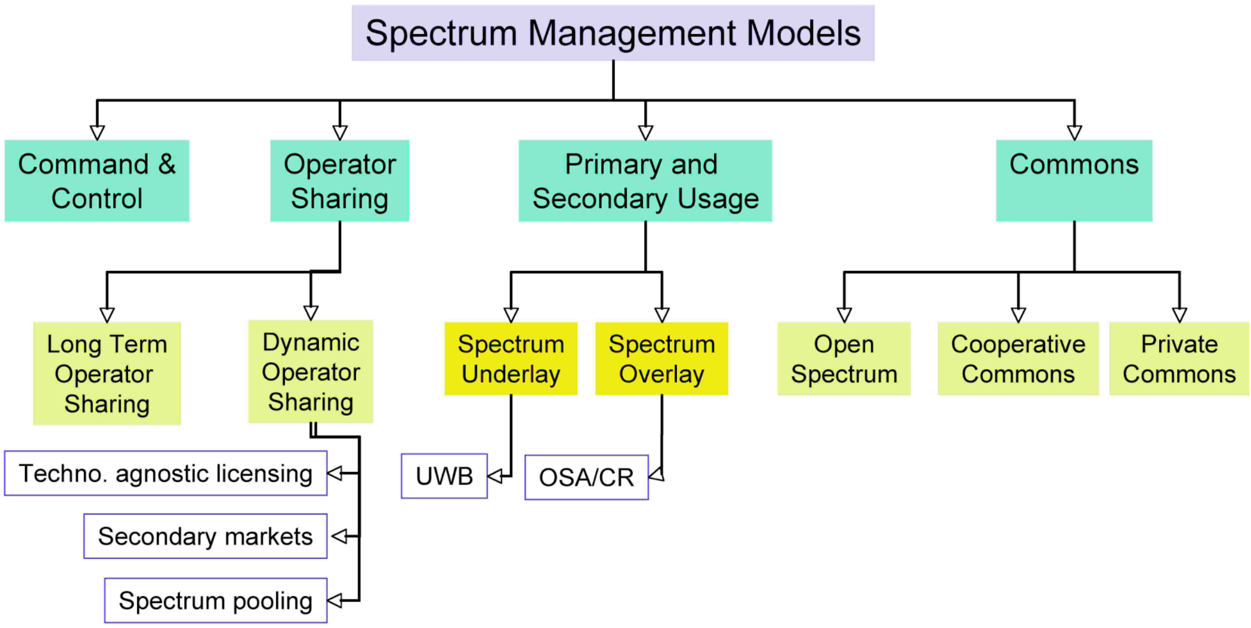

Figure 2.1 Classification of the Spectrum Management Models (adapted from [1]).

These classes are detailed in the following sections.

Some interesting key concepts are provided in [2] for characterizing models of spectrum access:

- **Transferable/non-transferable** transmission rights: a spectrum license is said to be transferable if the transmission rights can be transferred between actors without the explicit consent of the regulator. A priori, a non-transferable license can be transferred with the consent of the regulator but the time scale for such changes is so long that, from a technical point of view, we will assume that it is not possible.

- **Exclusive/Shared spectrum use/Commons**: this is related to the number of actors sharing the spectrum. Exclusive use means that a single licensee can access the spectrum. Shared use means that few users, possibly in cooperation, can access the spectrum. Commons means that many users can access the spectrum and all actors have the same rights to transmit.

- **Strict spectrum rules/etiquette**: the regulator may impose rules for the usage of the spectrum. If a spectrum band usage is subject to a given technology, like GSM, rules are strict. If the rule affects only power or power spectral density, like in the ISM band, or if rules are incentives for co-operation, we say that is only an “etiquette”.

- **Short/long term** spectrum usage rights: the characteristic describes for how long a license is attributed.

- **Centralized/de-centralized** technical solution: provides an idea of which type of technical solution would better meet the spectrum usage requirements. This is only an indication and should not influence the technical solutions proposed in the URC project. Note that [25] defines four grades of coordination among operators: “no coordination”, “one way” (one system can have information about spectrum use from another system but not vice versa), “two ways” (all systems are informed about the spectrum use of all other systems), “joint RRM” (a central entity manages the resources of all systems).

2.2 Command and Control

The class Command & Control is the less flexible class since the regulatory body has full control on the spectrum band, assigns the spectrum to some entity or usage for a quasi-eternal period of time. There is no notion of market or competition between different interests. This class is often depicted as "slow, inflexible, encouraging waste, with barrier to entry, bureaucratic"…(see e.g. [10]) although the best model choice for a spectrum band mainly depends on the spectrum band usage. Examples of such operation mode include indeed government, military use, radio astronomy or aeronautical operations.

Reference [9] has a quite extensive definition of the Command & Control regime and includes in this class any regime with harmonized spectrum, without service flexibility and without technology flexibility. We prefer to have a more restrictive definition of Command & Control (following [1] and [8]). This corresponds more or less to the first regime of [9]. In this regime, there are pure administrative procedures for spectrum assignment (to be opposed to procedures based on bidding price or beauty contest on the one hand, and to auctions on the other hand).

Reference [8] recommends to use Command & Control type of operation when public interests are at stake and give some examples:

"In general, command-and-control regulation should be reserved only for spectrum uses that provide clear, non-market public interest benefits or that require regulatory prescription to avoid market failure. For example, radio-astronomy may need to have dedicated, protected spectrum bands for foreseeable future, due to highly sensitive applications and the fact that its benefits accrue to society as a whole and only over the long run. Public safety and critical infrastructure may also require dedicated spectrum at particular times to ensure priority access for emergency communications. Other areas where limited use of command-and-control may be justified include international/satellite, public safety, and broadcasting."

Let us now review the key characteristics of **Command & Control**:

- **Non transferable**: access cannot transferred to a third party.
- **Exclusive use**: spectrum sharing is not possible.
- **Strict rules**: the regulator defines strict rules of operation.
- **Long term**: spectrum allocation is quasi-eternal.
- **Centralized**: spectrum allocation/control mechanisms are a priori centralized.
- **Examples**: government, military use, radio-astronomy, aeronautical operations.

2.3 Operator Sharing

A spectrum band is said to be under the Operator Sharing model if it has been licensed by the regulator to an operator, which has an exclusive use of the spectrum under certain limitations [1]. The owner has so exclusive rights on the band provided that it observes certain rules. These rules can be related to a type of service (e.g. voice), a technology (e.g. UMTS FDD), a region (e.g. WiMAX licenses in France), etc, or a mix of these items.

The spectrum allocation can be of long term (e.g. several years) or dynamic (e.g. with an order of magnitude of months, days, hours, or minutes).

In the **Long Term Operator Sharing** model, the regulator delivers licensees to operators for several years and only for a given technology and/or type of service. Inside its spectrum band, the operator has the possibility to perform a Fixed Channel Allocation (FCA) in order to manage interference. The share of a band with Dynamic Channel Allocation (DCA) between operators over a long term (like in DECT) is also classified in this mode of operation. Note that this sub-class should be a reference model for URC. Here are the characteristics of this sub-class:

- **Non transferable**: a band owner cannot transfer its license to a third party.

- **Exclusive use**: there is a single operator for the spectrum band.
- **Strict rules**: a single technology and/or a single service is possible in the band.
- **Long term**: the license is given for 10-20 years.
- **Centralized**: the operator manages its resources a priori in a centralized manner.
- **Examples**: GSM900, GSM1800, UMTS, DECT.

In the **Dynamic Operator Sharing** model, spectrum is still of exclusive use at a given point in time and space but the ownership may change. Sub-classes of this model are the Technology Agnostic Licensing, the Secondary Market model, or the Multi-operator Sharing model.

In Technology Agnostic Licensing, license is not subject to the use of a particular technology and so a given operator can use several technologies in the same band. This can be done at different time instants or different locations. A typical example of technology agnostic licensing is given in the DRIVE and Over-DRIVE project: an operator offers both broadcasting and/or UMTS services in the same spectrum band.

If Secondary Markets are allowed, the license can be rent or re-sold to a third party.

In the Multi-operator Sharing model, the band can be dynamically shared between several operators.

Here are the main characteristics of this class:

- **Transferable**: license can be transferred (Secondary Market or Multi-operator Sharing).
- **Exclusive use**: at a given time and on a given location, usage is exclusive for an operator. Contrary to the Commons case, there is a finite number of players.
- **Rules not so strict**: scenarios like “one operator, multiple technologies”, “multiple operators, one technology”, and “multiple operators, multiples services” are possible.
- **Mid-term**: month, day, hours. In the multi-operator sharing model, two levels should be distinguished : a long term allocation and a short term allocation. The long term allocation ensures resources to an operator, it can thus invest while limiting the risks. The short term allocation is done on a part of the spectrum that is shared with other operator. This term is intended to efficiently use radio resources.
- **Centralized**: a priori, there is coordination between operators or there is a spectrum manager (also called access broker [2]).
- **Examples**: DRIVE, Secondary Markets, DECT (Multi-operator Sharing).

The Long Term Operator Sharing model is called “traditional licensing” in [2]. It is close to regime 1 in [9].

The Dynamic Operator Sharing model is called “shared spectrum access” in [2] if the system is not based on real-time sharing. Moreover, it is explained that “the shared concept allows dynamic spectrum sharing, but without risking a complete breakdown, which could be the case with the commons. It is up to the licensees how to cooperate in the band” [2]. In the most dynamic case, where spectrum can be resold in real-time, the model is called “real-time spectrum exchange” in [2].

This model is also similar to the “exclusive use” model of [8]: “a licensing model in which a license has exclusive and transferable rights to the use of specified spectrum within a defined geographic area”. As the number of players is finite and cooperation is possible, this model reduces uncertainty compared to the Commons model [8].

Reference [4] refers also to the “dynamic exclusive use model” and proposes two sub-classes: spectrum property rights (similar to the Secondary Market approach defined above) and dynamic spectrum allocation (the same as Technology Agnostic Licensing approach defined above).

Secondary Market approach is similar to regimes 2, 5 and 8 of [9] ; Technology Agnostic Licensing is similar to regimes 4 and 7 ; Multi-operator Sharing is similar to regimes 3 and 6.

2.4 Primary and Secondary Usage

In this model, the spectrum band is owned by a primary user, but the band can be opportunistically used by a secondary user with minimum impact on the primary user [1]. In the ideal case, the primary user is not even aware of the secondary user transmissions.

According to the type of technology used by the secondary user, sharing is called **Spectrum Underlay** or **Spectrum Overlay**. In the former case, power levels used by the secondary user are so weak that there is no interference for the primary user. The use of UWB falls in this sub-class. In the latter case, access is opportunistic (in time or space) so that this approach can be called "opportunistic spectrum access (OSA)", "listen-before-talk" (in relation with the type of MAC protocol that can be used), "cognitive radio" (CR, e.g. in [5], although the term CR is far more generic, it is sometimes mixed up with the term "opportunistic access" because this is the approach proposed by Mitola in [11]), or "spectrum pooling" [4][12]. Here are the main characteristics of this class:

- **Not transferable**: the primary user does not transfer rights to the secondary users but rather tolerates its transmissions provided that the impact is negligible.
- **Non exclusive use**: secondary users can access the spectrum band.
- **Rather strict rules**: regulator imposes strict rules to the primary user, primary user imposes rather strict rules to the secondary user.
- **Short term**: ms or s is an order of magnitude for the secondary user access.
- **Decentralized**: the secondary user is a priori decentralized.
- **Examples**: UWB (underlay), DARPA xG program (overlay).

References [5] and [25] give the name of "vertical spectrum sharing" to overlay because "users are on different levels with regards to their rights to access shared spectrum". Reference [4] has another name for this model: "hierarchical access model". Sub-classes are however also named "spectrum overlay" and "spectrum underlay". Reference [25] proposes also "prioritized spectrum access".

2.5 Commons

In this model, no entity can claim the exclusive use of a frequency band (seen as a public resource) and any one can access for free the resource provided that basic rules are observed [1]. The number of players is not finite a priori. The spectrum usage is not constraint to a specific service.

According to the type of rules, it is possible to further distinguish between three sub-classes: **Open Spectrum** (or "uncontrolled access", if rules are minimal like those of the ISM band), **Cooperative Commons** (an etiquette imposes rules to avoid the so called tragedy of commons, i.e., a collapse of the system because of uncoordinated and anarchical access), **Private Commons**.

In this latter sub-case, there is a license holder for the spectrum band. This holder allows opportunistic access to its spectrum only with a specific technology or protocol. As a consequence, there is no exclusive use of the band, there is no primary user (since all users have equal access), but rules are rather more strict than in the other commons sub-classes.

Here are now the characteristics of the Commons:

- **Not transferable**: this concept does not apply to this model.
- **Non exclusive use**: by definition of the commons.
- **Short term**: ms or s is the order of magnitude of the access procedures.
- **Decentralized**: a priori, the access methods are decentralized.

- **Examples**: ISM band (open access), 3650 MHz band for US Wireless ISP [1] (cooperative commons).

The Commons model is included in regimes 3, 6 and 9 in [9] with the term “collective use”. Reference [9] has a “California dream” regime, which is the most open and the most flexible (so suggesting without proof that it is the most efficient). In [2] and [4], only the “open spectrum access” is defined, the two other sub-classes being ignored.

Reference [8] provides a detailed definition of the “commons” model or “open access” model: “it allows unlimited numbers of unlicensed users to share frequencies, with usage rights that are governed by technical standards or etiquettes but with no right of protection from interference”.

It is often said that this model “leads to greater technological innovation and spectrum efficiency than an exclusive use approach” [8] because users have incentives to efficiently use the spectrum.

2.6 URC Scenarios

Let us now shortly review the URC scenarios with regards to this classification.

- Command & control and long term operator sharing models are clearly benchmark models for URC.
- SC1: Free License Network. This scenario is related to the Commons model (probably open access and cooperative commons sub-cases).
- SC2: Wireless Local Loop. This scenario is related to Dynamic Operator Sharing model regarding roaming in 2.6 and 3.5 GHz bands. The sharing between UMTS and WLL in the 2.6 GHz band is rather Private Commons.
- SC3: Analog to digital TV migration. This scenario may be related to the Primary and Secondary Usage model.
- SC4: Exceptional event. This scenario is related to spectrum share between operators and so to the Dynamic Operator Sharing model.
- SC5: Major crisis. This scenario is also related to the Dynamic Operator Sharing model.
- SC6: Metropolis. This scenario is not yet sufficiently detailed.

3 State of the Art on Dynamic Spectrum Access

3.1 Regulation

Regulation regarding spectrum allocation is based on a stratified approach: global decisions at a worldwide level are handled by ITU through the process of WRC and RR; application at a regional level is performed e.g. CEPT in Europe, and then application at a national level is undertaken by national regulator. In France, ANFR and national entities for service related allocation, called “Affectataires” (ARCEP for telecoms, CSA for broadcast, and state related entities: Defense, Aviation, Police, PPDR, …) are in charge of spectrum regulation.

Practically, allocation and control are performed at a national level, and spectrum is considered as a national resource.

In telecommunications, two main processes are involved most of the time to allocate spectrum to users. Allocation is either performed through a “beauty contest”, or is performed through an “auction process”.

The band (spectrum) is allocated to user either through a **license** (for a private company, for example an operator) or through an **allocation**, for example to police or firemen services[1].

- Beauty contest : it is a call for tender, in which all the offers have to respect a frame edited by the regulator. All the offers are evaluated according to a set of criteria, such as the time table to reach a given coverage (geographic or population), the type of services which are to be proposed, the cost which is to be paid to get the license, etc. The cost of the license may be fixed by the regulator; in this case it is no longer a criterion to compare the offers. This process has been used in France for 2G and 3G networks.
- Auction : in an auction the services which are to be proposed through the use of the frequency band is usually defined, but not necessarily mandatory. The license obtained by the highest bidder, and the technical constraints (coverage, services, …) are usually weak.

Whatever the process involved for allocation – auction or beauty contest – different types of use are attached to the allocation :

- Exclusive use : the user is the only entity who can use this portion of spectrum
- Primary and secondary usage : primary usage implies a notion of priority. Secondary usage has the obligation not to interfere with primary usage.

Today, the whole spectrum is allocated, and many situations of sharing exist, but this sharing is based upon studies made once and for all, without dynamic features, and respecting the notion of primary and secondary use.

A second market has been recently allowed in France for the 3.4 – 3.6 GHz band, for WIMAX based WLL services. In this band, two licenses have been awarded for the French administrative region. It is possible for a licensed operator to resell the whole license or only part of it. Reselling the whole license means the rights and the obligation attached to the license. In WIMAX, this means the right to propose fix and nomadic services, and obligation to respect a time table regarding coverage. Reselling part of it may concern parts of the geographical area on which the license is valid, or part of the frequency band concerned by the license, or the duration over which the license is valid. It is also possible for an operator to keep the complete license, while authorizing another entity to use the frequencies. In this case, the owner of the license remains responsible for the fulfillment of the obligations attached to the license. The entire process is supervised and authorized by the regulator (ARCEP).

The English regulator, OfCom, proposes a comparable frame under the name of spectrum trading. The global conditions are quite equivalent, except in total transfer, the rights and obligations can be shared or not. In fact, the main difference is that many licenses are made tradable in the UK, as shown in [52] : cellular, PMR, WLL, PtP, are licenses which are tradebale.

Basically, the spectrum is the property of the state/government. The state decides of the part which are used by the services dependant on the administrations (civil aviation, defense, PPDR, etc), and allows other users (private companies, private persons, non profit organizations) to use some parts of the spectrum, for commercial use or not.

We may consider in the frame of URC that the precise conditions of use of the some bands in the radio spectrum could change, with more flexibility implying more efficiency (which has probably still to be proved), but the global frame is due to remain the same : the spectrum is the property of the state, and private users (in the global meaning) have some licenses for some bands.

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[1] Of course the word “license” implies the notion of allocation of a portion of spectrum but, in the situation of Command and Control type of use, for government users, it is clear some spectrum is allocated, but there is no “license” of use.

3.2 Standards

3.2.1 P1900

The information presented here is mainly based upon the presentation “Standard IEEE P1900.4 Allocation Dynamique de Spectre (DSA) et radio cognitive » by P. Houzé, France Télécom R&D, at URC’s seminar, 16/10/07.

IEEE P1900 goal is to set up standards for "*new technologies and techniques being developed for next generation radio and advanced spectrum management*".

Group	**Scope**
IEEE P1900.1	*Terminology about advanced radio concept*
IEEE P1900.2	*Recommended Practice for Interference and Coexistence Analysis*
IEEE P1900.3	*Recommended Practice for Conformance Evaluation of Software Defined Radio (SDR)*
IEEE P1900.A	*Dependability and Evaluation of Regulatory Compliance for Radio Systems with Dynamic Spectrum Access*
IEEE P1900.4	*Architectural building blocks enabling network-device distributed decision making for optimized radio resource usage in heterogeneous wireless access networks.*

The objective of the standard IEEEP1900.4 is to define the process of decision making, and to distribute this process between the network and its terminals. This requires the definition of RRM protocols accounting for :

- Network optimization constraints
- radio **environment**
- User parameters: required QoS, profile, battery, etc.

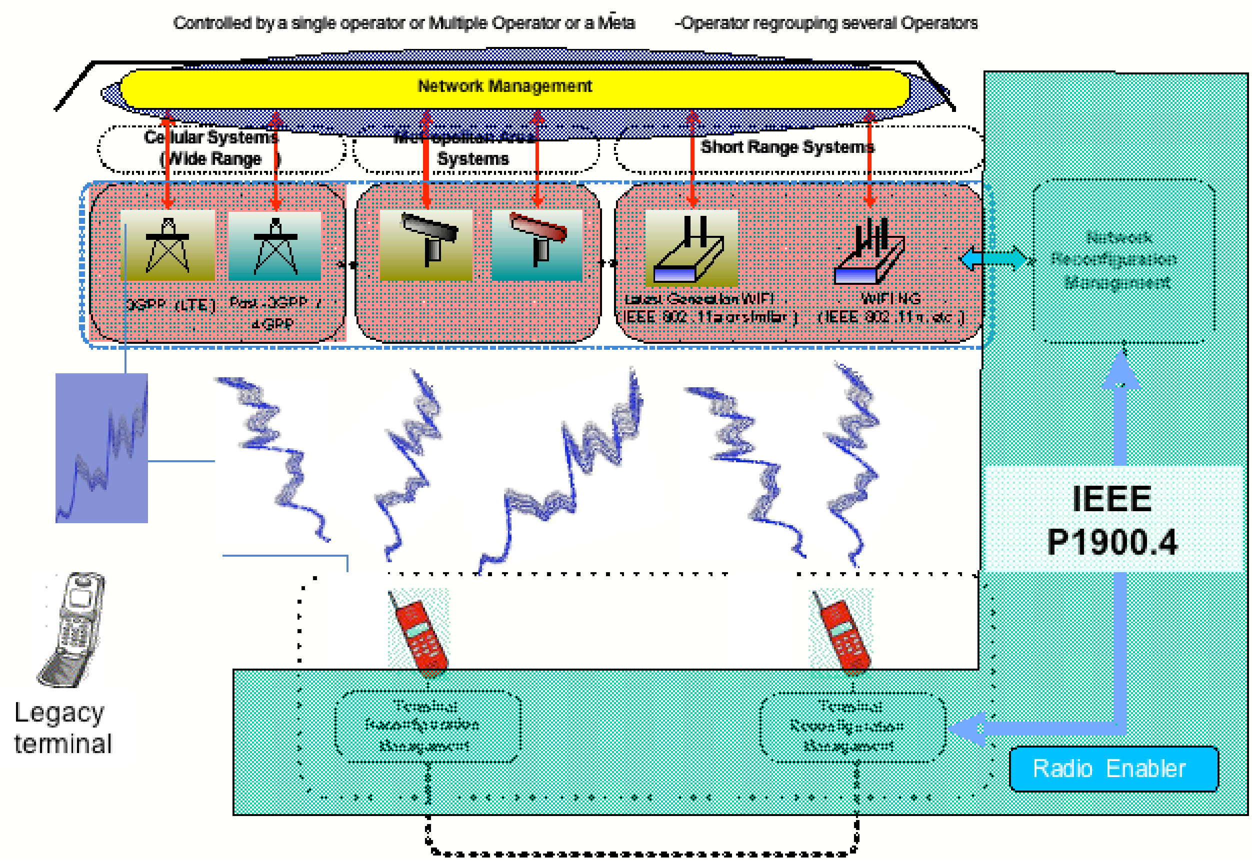
The technical approach to reach this goal follows these principles :

- Terminals make their own decision in an autonomous way, within the frame of the constraints defined by the network.
- The network controls the global optimization of the resources, but do not support all the individual decisions which are to be taken at the terminal level.
- Constraints are called *Policies* and are sent to the terminals through a Radio Enabler.
- The standard will define protocols and information flow.

The challenge is to propose a standard which improve significantly the optimization of radio resources ibn heterogeneous networks, with dynamic spectrum allocation.

The Proposed System Concept is summarized on the next figure. The situation assumes several RATs, all of them managed through a dedicated, common network. The P1990.4 structure brings the TRM and NRM, in charge of configuring properly and simultaneously the networks and the terminals.

The system may be controlled either by a single operator, an association of operators or a meta-operator".



Policies are defined by the Network Reconfiguration Manager (NRM) in a unified way, and sent to terminals by RE. Here is an example of a policy structure :

{Policy ID,

{ Rule ID 1,

{condition1},

{action1.1}{priority (may/shall/shall not)},{Timer expression1}}

OR

{action1.2},{priority (may/shall/shall not)},{Timer expression1}},

.....

{ Rule ID 2,... }}

The content send by the Radio Enabler is related to contextual information regarding spectral allocation depending on the date and place.

Ex : {in place=(x,y), RAT1 at frequency F available}

Policies to prepare to change allocation :

- "emptying" a frequency band:
    - inter-systems mobility forbidden toward this band
    - handover mandatory from this band.

Different use cases can be considered according to the strategy of P1900.4. Three of them are presented below.

1900.4 – Use case I : Dynamic Spectrum Allocation

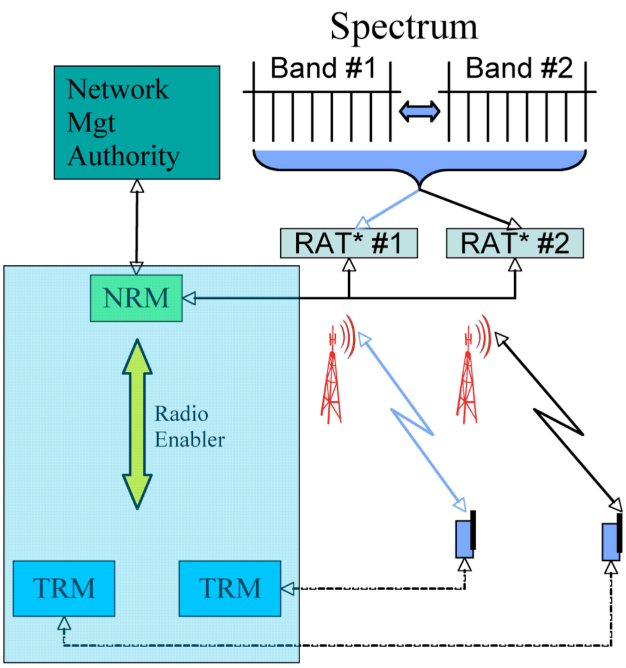


Figure 3.1 - Dynamic Spectrum Allocation

The allocation of the bands is modified between the RATs at the network level. This leads to a dynamic assignment do base stations. P1900.4 provides the information flow to reconfigure the network and the terminals.

Classification: The corresponding type of sharing could be "Dynamic operator sharing / Technology Agnostic Licensing", or "Private commons". "Shared use / Underlay" could be relevant as well, for the Radio Enabler.

1900.4 – Use case II : Dynamic Spectrum Access

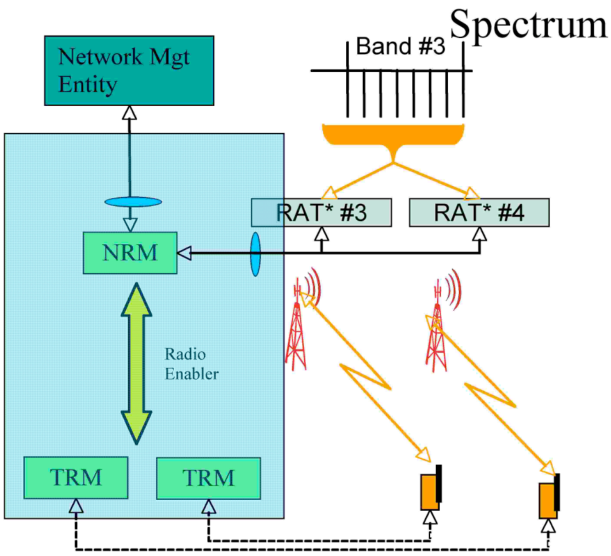


Figure 3.2 - Dynamic Spectrum Access

In this use case, the same portion of spectrum is used by two different RATs, one being primary user. Secondary users may access dynamically the resources without causing interference to primary ones, using P1900.4 information flow to manage access restrictions to the spectrum at considered locations.

Classification: this type of sharing can be classified into "Dynamic Operator Sharing / Technology Agnostic Licensing" or "Dynamic operator sharing / Multi-operator Sharing". "Private commons" is another possibility. But "Shared use / Underlay" could be relevant as well, for the Radio Enabler.

1900.4 – Use case III : Distributed Radio Resource usage optimization

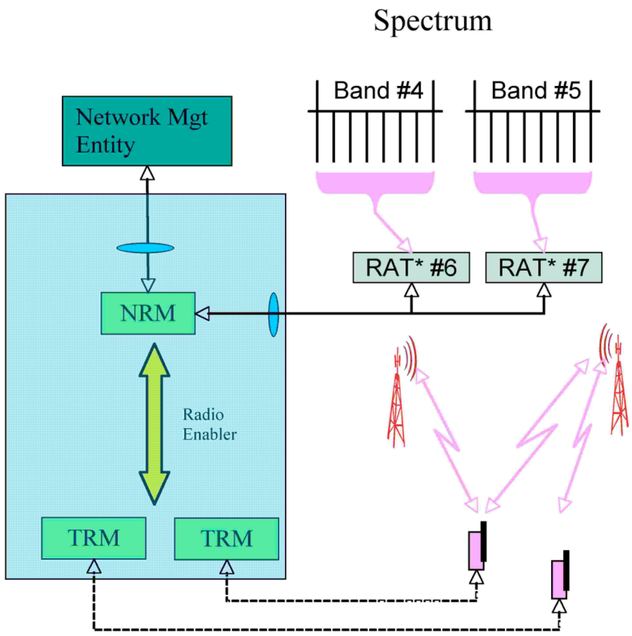


Figure 3.3 – Distributed radio resources

This use case is dedicated to the optimization of distributed radio resources between RATs and services, at two levels :

- At the network level, global objectives are defined. The network derives policies according to these objectives.
- At the terminal level, terminals make decision according to local parameters, within the frame of the global constraints defined by the policies.

Classification: This use case is difficult to classify regarding spectrum use, because there no spectrum assignment, but rather the assignment of a given RAT to a given service. Of course, we may consider that a RAT uses a frequency band, so the spectrum assignment is implicit, but this implicit character is precisely what makes it difficult to classify. In fact, this use case is more commonly named joint radio resource management.

3.2.2 IEEE 802.22

IEEE 802.22 is a new IEEE 802 working group formed in 2004. “The WG is chartered to develop a standard for a cognitive radio-based PHY/MAC air interface for use by license-exempt devices on a non-interfering basis in spectrum that is allocated to the TV Broadcast Service”.

The standard is specifically developed to use locally vacant TV channels in the TV broadcast bands between 54 and 862 MHz. Better RF propagation in these VHF and UHF bands shall enable Broadband Access over longer distances in particular to serve rural areas.

The technology will include cognitive radio features that will consist in sensing the presence of television broadcast signals in the area and avoid potential interference by automatically selecting an unused television channel for its operation. [31]

Fixed devices could be deployed with an Effective Isotropic Radiated Power (EIRP) of up to 4 Watts.

So, some controls would need to be implemented in order to mitigate the potential interfering effects on TV broadcast operation. The devices would need the ability to determine if a channel is used before it could transmit (control signal, sensing, geo-localization, etc.) and it would need to be able to move off a previously vacant channel if the licensed user starts to transmit.

The range of frequencies (54 MHz to 862 MHz) covers all the TV broadcast bands allocated in the world and the three TV channel bandwidths (6, 7 and 8 MHz) are being considered.

An example of service model is summarized in Table 1 for a 6 MHz TV channel bandwidth. As it can be seen, the service proposed for each subscriber terminal is 1.5 Mbit/s downstream and 384 kbit/s upstream, allowing for typical Internet data services including videoconferencing.

Typical WRAN service model		
RF channel bandwidth	6 MHz	
Typical spectrum efficiency	3 bit/(s*Hz)	
Channel capacity	18 Mbit/s	
Per subscriber capacity (forward)	1.5 Mbit/s (peak min.)	
Per subscriber capacity (return)	384 kbit/s (peak min.)	
Over-subscription ratio	50:1	
Subscribers per forward channel	600	
Minimum viable operation		
Minimum number of subscribers	90	
Initial penetration	5 %	
Potential full penetration		
Potential number of subscribers	1,800	
Number of person per household	2.5	
Population per coverage area	4500	
Type of operation	**USA**	**Other?**
WRAN base station EIRP limit	4 Watts	100 Watts (?)
WRAN user terminal EIRP limit	4 Watts	4 Watts (?)
Coverage radius	16.7 km	30.7 km
Minimum population density	**5.1** person/km^2	**1.5** person/km^2

Table 1: Example of assumed WRAN service model

The key technical parameters such as the frequency range of 54-862 MHz, the three applicable TV bandwidths, the extent of coverage for the PHY under typical propagation conditions (30 km), the maximum extent of coverage supported by the MAC for ideal propagation conditions (100 km), and the expected transmission channel time spreading for which the standard is being developed (33 µsec excess delay multipath) are indicated.

The standard is expected to be delivered to the industry in early 2008 and the resulting technology should be especially well suited for deployment rural areas and developing countries.

It is anticipated that equipment that will comply with this new standard will start to appear on the market in 2009.

3.2.3 IEEE 802.16

3.2.3.1 IEEE 802.16d/e

The standard IEEE 802.16d [28] augmented by the features of IEEE 802.16e [29] has defined several air interface for license bands: WirelessMAN-SC, SCa, OFDM, OFDMA. We will here consider only OFDMA air interface.

There are several traditional ways of managing the spectrum in IEEE 802.16 networks: sub-carriers can be grouped with different methods to form sub-channels, traditional frequency reuse patterns enable to reduce interference, scalable OFDMA is a flexible way of managing the operator bandwidth.

There are two main methods to group sub-carriers into sub-channels: the diversity modes (PUSC and FUSC) and the contiguous allocation (AMC). As shown on the following figure, diversity modes assign to a sub-channel sub-carriers taken in a quasi-random way along the whole bandwidth. This technique allows an kind of averaging of the sub-carrier radio qualities. On the contrary contiguous allocation modes assign contiguous sub-carriers to a sub-channel. This technique allows an opportunistic allocation as function of the channel radio quality.

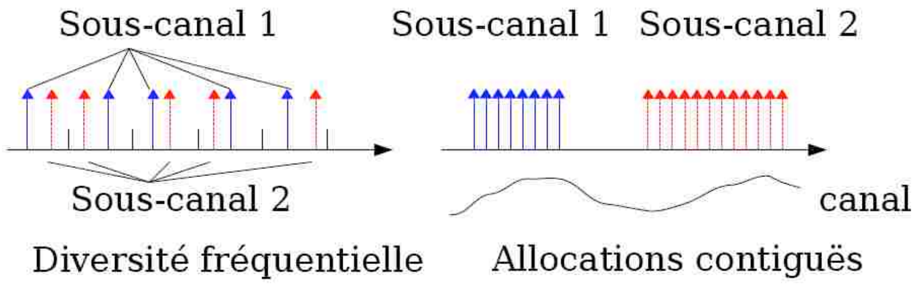


Figure 3.4 Sub-carrier assignment modes in IEEE 802.16.

Frequency allocation to cells can be done in a traditional way by assigning different frequency bands to adjacent cells. A given band can also be segmented using the PUSC permutation. As shown on the following figure, sub-carriers can be partitioned (or segmented) and assigned to different cells (here three cells). A “fake” reuse 1 is so possible with this method.

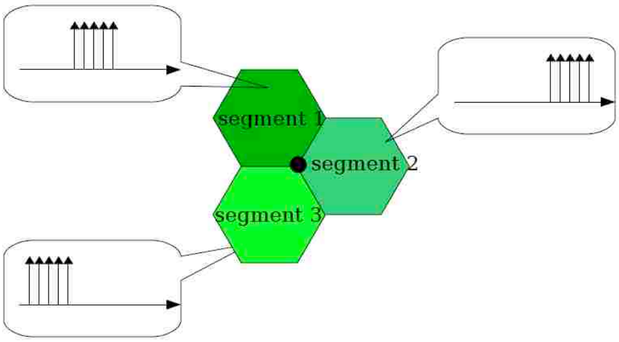


Figure 3.5 Segmentation in IEEE 802.16.

The principle of SOFDMA is shown on the following figure: there is a constant frequency spacing between sub-carriers whatever the bandwidth allocated to the operator (the number of sub-carriers scales with the bandwidth). The different bandwidth sizes proposed by the standard allows several usages of the technology and an easier spectrum allocation by country or region. It is also a way of reducing the product cost.

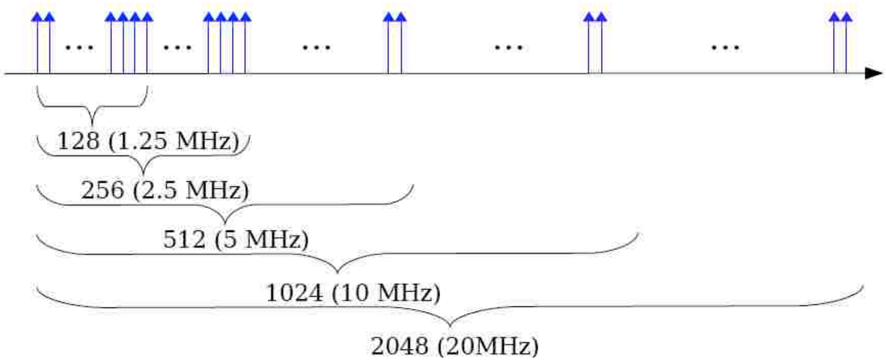


Figure 3.6 Principle of Scalable OFDMA in IEEE 802.16.

On top of these features (frequency reuse, sub-carrier permutations, segmentation, scalable OFDMA), the standard IEEE 802.16d/e has defined a **Dynamic Frequency Selection** (DFS) mechanism for the unlicensed bands (the air interface is called WirelessHUMAN for High Speed Unlicensed Metropolitan Area Networks). Note that in IEEE 802.16e, DFS is also called “Procedures for shared frequency band usage”.

The aim of the DFS is to facilitate the detection of other users and to avoid or prevent harmful interference to other users in the same band. The DFS shall also allow spectrum sharing with specific users identified by the regulator. Such a "specific spectrum user" (SSU, a "primary user" in the terminology of this document) would require a special protection from harmful interference. DFS includes the following functions:

- Testing channels: a BS or a SS are able to test channels to assess the presence of primary users.
- Discountinuing operations: if a primary user is detected, transmissions MAC PDU has to be stopped.
- Scheduling of channel testing: a BS may request any SS to measure a channel and so should not send any data to that SS or schedule this SS during measurements.
- Requesting and reporting of measurements: there is a hand-shake mechanism between BS and SS to request and report measurements.
- Selecting and advertising a new channel: the BS is able to stop operating a channel and switch to a new channel, it is also able to advertise the SS of this.

3.2.3.2 IEEE 802.16h

IEEE 802.16h is a new standard in preparation. Today, only a draft is available [30]. This draft extends the WirelessHUMAN DFS mechanisms (they allow **uncoordinated coexistence**) and define a new air interface, called WirelessMAN-CX with **coordinated coexistence** mechanisms.

For uncoordinated coexistence (WirelessHUMAN), the draft distinguishes two main cases:

- Coexistence with a SSU (or primary user): DFS mechanism (it is the same as in 802.16d/e but much more details are given) has to be used.
- Coexistence with non-SSU: a Dynamic Channel Selection (DCS) mechanism and a Uncoordinated Coexistence Protocol (UCP) have to be used. The main difference with the previous case is the fact that regulation requirements are less stringent. For example, if a non-SSU is detected, it is not mandatory to vacate the channel; rather a more robust modulation or AAS can be used.

For more details on DFS, DCS and UCP, the reader can read reference [30] section 6.4.

Besides the uncoordinated case, the standard specifies mechanisms that mainly aim at reducing the interference between WirelessMAN-CX systems in a coordinated manner. There are three basic mechanisms for coordination coexistence:

- MAC frame synchronization with transmit and receive intervals for separating BS and SS transmissions.
- Dynamic and Adaptive Channel Selection (DCS and ACS) for finding less interfered frequencies.
- Separation of the remaining interference in the time domain: several operators can thus share the same frequency channel.

The inter-BS communication is done through a Coexistence Protocol (CXP). More on these mechanisms can be found in [30] section 30.

3.2.3.3 IEEE 802.16m

Few information is today available on what will be the IEEE 802.16m standard. Only a draft on requirements of the system [27] gives some hints about how spectrum is managed. IEEE 802.16m shall support scalable bandwidth from 5 to 20 MHz and operate in frequencies less than 6 GHz (like any mobile system) in the frequencies identified for IMT-Advanced. The system should be able to use spectrum flexibly to provide TDD and FDD duplex modes. There are of course coexistence requirements with other technologies. Interoperability with IEEE 802.16e-2005 systems is required:

- A 802.16m MS shall be able to operate with a 802.16e BS,
- A 802.16m system and a 802.16e system shall be able to operate on the same carrier with the same or **different channel bandwidths**,
- A 802.16m BS shall be able to support both 802.16m and 802.16e MS,
- Hand-overs from and to 802.16e system shall be supported,
- A 802.16e MS shall be supported by a 802.16m BS.

It should be able to **aggregate multiple channels in more than one frequency band** within the scope of a single MAC protocol instance. IEEE 802.16m shall support **interference mitigation** schemes and **flexible frequency re-use** schemes.

Several coexistence scenarios are envisaged:

- 802.16m and non-802.16m systems have equal access as primary users in the same licensed band but short term spectrum sharing is not possible,
- 802.16m and non-802.16m systems have equal access as primary users in the same licensed band and short term spectrum sharing is possible,
- 802.16m is the secondary user of a non-802.16m system. Access can be coordinated or not, on a co-channel basis or not.

Technologies to support these requirements [27] are not today available and are under development.

3.3 Existing Systems

3.3.1 Classification of conventional channel assignment methods: FCA, DCA, HCA

Channel assignment is usually classified in three categories: Fixed Channel Assignment (FCA), Dynamic Channel Assignment (DCA) and Hybrid Channel Assignment (HCA).

In **FCA**, channels are subdivided in frequency sets, each of which allocated to a group of cells and reassigned to other groups of cells according to some reuse pattern. Each BS is allocated a fixed set of frequencies in planning phase and allocation does not change over time. This frequency assignment method is simple but not easily adaptable to varying radio/traffic conditions.

Under **DCA**, channels are assigned on demand and dynamically depending on propagation and traffic conditions. Channels are placed in a pool and dynamically assigned to calls in order to optimize a cost function such as: likelihood of blocking on this channel, maximization of carrier to interference ratio, ….

HCA is a combination of both FCA and DCA: some channels are pre-assigned, others are shared dynamically. Different approaches can be envisaged for example consisting in borrowing some channels from neighbouring cells when its own channels are occupied.

3.3.2 Channel Allocation: implemented

3.3.2.1 GSM/DCS 1800 (FCA)

In GSM/DCS1800, the air interface is characterized by eight-order TDMA scheme with frequency division duplex (FDD). The available frequency band in Europe is 2x25 MHz (890-915 MHz for Uplink, 935-960 MHz for Downlink) with a radio channel spacing of 200 kHz.

The available frequencies are divided into groups and fixedly allocated to different cells. The reuse distance depends on the maximum tolerable co-channel interference. The frequency groups are reused by cluster cells that are sufficiently far away from each other. The reuse distance depends on the maximum tolerable Carrier to Interference ratio.

3.3.2.2 UMTS (FCA)

3 carriers: 1 for R'99, 1 for HSDPA and another one

3.3.2.3 US IS-136 (Quasi Static Frequency Allocation)

This technology performs dual mode: cellular/cordless. Frequencies and modulation schemes are common to both scenarios.

It is envisaged that when the cellular phone user comes into the coverage area of the personal base station, all cellular calls to and from the handset are rerouted to the personal base station unless personal base station is already occupied. In this case, the cellular phone conversation continues to use the cellular base station.

Empty channels are selected to ensure that other cellular phone users remain unaffected: channels are constantly scanned and the level of interference is monitored.

A cost is then associated with the level of interference on each channel, updated each time the channel is scanned. A channel with the lowest cost is selected for use. The cost is also used to determine how frequently the channel should be used. The particular cost values chosen ensure that a channel is only selected if it has been empty for one or two days and given up very quickly (seconds) if interference increases because it has been selected by the cellular operator. The initial frequency allocation is sent to the personal base station over a land-line, which has the advantage that the allocation can be changed at any time.

3.3.2.4 DECT (DCA)

The DECT (Digital Enhanced Cordless Telecommunications) system is designed for short-range use as an access mechanism and offers cordless voice, fax, data and multimedia communications, wireless local area networks and wireless PBX. DECT operates in the 1880 to 1900 MHz band.

The entire 20 MHz need not be employed by DECT-based systems. DECT makes efficient use of the assigned radio spectrum, even when multiple operators and applications share the same frequency spectrum. [32]

There are 10 frequencies of operation in these 20 MHz band (MC Multi-Carrier system), with a spacing of 1.728 MHz. In addition to this, the time dimensions for each carrier is divided to provide timeframes repeating every 10 ms. Each frame consists of 24 timeslots, each individually accessible. These slots are divided into two groups of 12 slots each, one group for each direction of transmission.

A total spectrum of 120 duplex channels is then available to a DECT device at any instant location.

DECT is based on TDMA/TDD principles. Apart from the conventional TDMA systems, all the slots in the TDMA frame need not be transmitted on the same frequency. This variation is called Multi-Carrier TDMA. Each of the 12 slots could be on a different frequency, though the pair of slots used for each link must be on the same frequency.

DECT features continuous Dynamic Channel Selection and Allocation which guarantees that radio links are always set up on the least interfered available channels.

Channel selection takes place at the mobile only. The handset locks on the strongest BS by examining the beacon frequencies transmitted on a control channel from the base station. The mobile scans sequentially (at least once every 30s) the 120 channels and selects the one that has the highest CIR. The BS is notified of the chosen channel which is then used for the subsequent conversation.

3.3.3 Channel allocation in heterogeneous radio configuration

An optimized and cost effective usage of networking has to be been realized through inter-working between different technologies. Network inter-working eventually in overlapping radio coverage calls for co-existence between different radio technologies.

This subject has been widely studied over the last fifteen years:

- WiFi with Bluetooth or
- WiFi with Radar
- DECT with UMTS,
- etc.

These coexistence studies aim at assessing the max interference level that can be tolerated by each system.

Inter-working solutions then consist in

- either mitigating interference by specific radio processes such as adaptive antennas, beamforming ,
- or by avoiding inter-system interference:
    - Preventing simultaneous transmissions thanks to a “minimum guard time” between transmissions at the same frequency.
    - Limiting excessive interference by spacing sufficiently (minimum reuse distance of the channel) BSs operating at the same frequency.
    - Avoiding frequency collision thanks to Dynamic Spectrum Assignment.

In the following, here some examples of Dynamic Frequency Allocations schemes in a multi-radio technology environment.

3.3.3.1 The unlicensed ISM band - WiFi/Bluetooth – 802.15 WG

Wi-Fi and Bluetooth wireless technology both share a section of the 2.4 GHz ISM band that is 83 MHz-wide: the 22 MHz wide Wi-Fi channel occupies the same frequency space as 22 of 79 Bluetooth channels which are 1 MHz wide.

So, when WiFi and Bluetooth devices are located in close physical proximity to one another, there is concern for how they may interfere to one another.

Since neither Wi-Fi nor Bluetooth was originally designed with mechanism in place to deal with the interference generated by others, many engineering studies have been performed to examine the effects of Bluetooth on Wi-Fi, and vice versa.

These studies have shown that until “new mechanisms” to facilitate coexistence of the two technologies are implemented, the only solution is to physically increase the space between the two networks or adjust signal level to reduce interference.

Here is how Bluetooth and WiFi independently manage coexistence.

When a Bluetooth device encounters interference on a channel, it hops to the next channel and tries again up to the next idle channel. This results in a degradation of data throughput for Asynchronous Connection-Less and in packet loss for Synchronous Connection Oriented (SCO) like voice.

WiFi implements the CSMA/CA access protocol: a mechanism of collision avoidance based on mutual acknowledgement between transmitter and receiver. Each station that wants to transmit, first senses the radio channel. It the channel is busy, transmission is differed. Otherwise, medium is considered free during a given time (Distributed Inter Frame Space). The station is authorized to transmit.

The Bluetooth SIG and the IEEE 802.15 working group for Wireless Personal Area Networks are collaborating on efforts to define mechanisms and recommended practices to ensure the coexistence of Bluetooth and Wi-Fi networks. These practices fall into two categories:

- collaborative mechanism in which the wireless personal area network and the WLAN communicate and collaborate to minimize mutual interference
- non-collaborative mechanism in which there is no method for the WPAN and the WLAN to communicate but non-collaborative techniques being investigated are Adaptive packet selection and scheduling (based on statistics on channels that encounter interference) and Adaptive frequency hopping (classifies channels and alters the regular hopping sequence to avoid channels with the highest interference).

3.3.3.2 WiFi/RADAR coexistence (DFS/TPC)

The Dynamic Frequency Selection along with Transmit Power Control have been adopted by the US, Japan and Europe to enable WiFi device to share 5GHz spectrum with Radar systems.

Regulation in the 5 GHz band

The regulation institutions have distinguished between 4 sub-bands bands for use of RLANs:

- The low band: 5.15-5.25 GHz, the middle band 5.25-5.35 GHz.
- The high band: 5.47 - 5.725 GHz and the upper band : 5.725 - 5.85 GHz.

The upper band is only reserved in the US. In Europe, the low, middle and high bands are reserved, which corresponds to 19 channels.

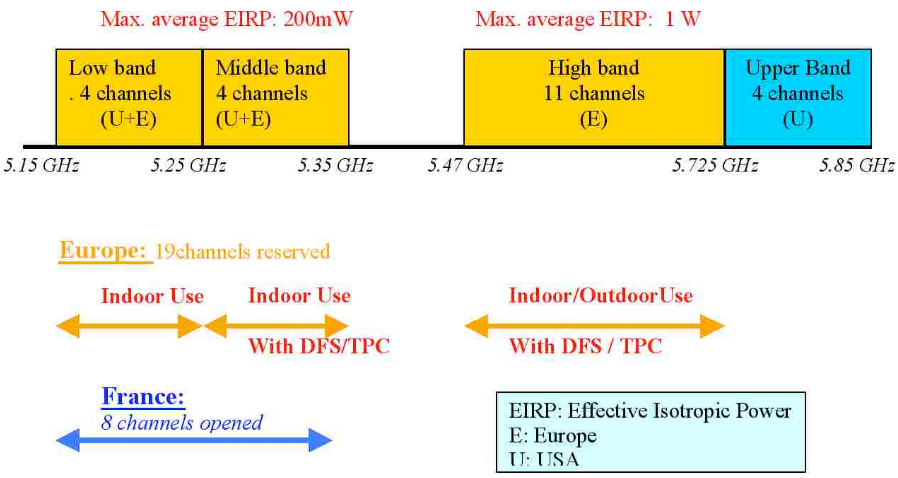


Figure 3.7 Regulation status at 5 GHz (before WRC 2003).

As illustrated in Figure 2, regulatory requirements for use of these RLANs include:

- the maximum Effective Isotropic Radiated Power,
- whether usage is restricted or not to Indoor,
- whether Dynamic Frequency Selection (DFS) and Transmit Power Control (TPC) have to be supported so as to enable non harmful coexistence with other systems such as radiolocation systems used by ministry of defense, meteorology systems…).

DFS target capabilities

DFS is the process originally intended to mitigate interference among uncoordinated RLAN clusters (for spectral efficiency optimization). DFS capabilities then consisted in detecting Radar systems that have to be protected against WiFi interference and upon detection in switching the operational WiFi frequency to another one that is not interfering with radar systems. DFS equalizes the probability of selection of all the available channels in order to guarantee a uniform repartition of the spectrum loading.

Standardization

Three standardization bodies have been involved in the specification of the DFS technical requirements:

- The ITU-R issued a recommendation on DFS mechanism used as a mitigation technique to enable sharing with incumbent systems: radars.
- The Harmonized European Standard (EN 301 893 harmonized standard) produced by the ETSI/BRAN committee defines the types of waveforms that RLANs operating in the 5GHz band should detect as well as threshold and timing requirements.
- In a supplement draft to the IEEE standard 802.11l written by the IEEE committee, interference mitigation techniques (DFS and TPC) are specified at PHY and MAC layers so as to cope with European regulatory requirements for operation in the 5 GHz band.

Technical requirements for use of the 5GHz band by RLANs device include:

- Detection requirements: the DFS mechanism shall be able to detect a pulse signal above a minimum Interference Threshold.
- Operation requirements: prior to use any channel for transmission and if no Available Channel has yet been identified, the RLAN system shall monitor the channel with the detection mechanism within Channel Availability Check Time to check its availability (no used by other systems such as Radars). Once the RLAN system starts to operate on an Available Channel then this channel becomes the Operating Channel. During its in-service operation or normal operation, the DFS shall monitor the Operating Channel within Channel Availability Check Time to check if a radar has started operations within the frequency range of the RLAN. The revalidation period is defined by the Channel Revalidation Period.
- Response requirements: the RLAN shall cease normal transmissions on the Operating Channel within Channel Move Time if this channel has been flagged as containing a radar. Transmission shall be completed during the aggregated transmission time, noted Channel Closing Transmission Time. When an Operating Channel has been flagged as containing a radar signal, the RLAN device cannot use the channel during a Non-occupancy Period.

3.3.3.3 DECT/Radio technologies

The coexistence properties of the radio access technology of DECT mainly relies on the ability to escape (handover) - in the frequency domain – from the interfered radio link, not relying on information transferred over the original (interfered) channel. MC/TDMA/TDD, continuous Dynamic Channel Selection and Allocation and the handover procedures in the DECT standard show excellent coexistence properties even under heavy interference conditions.

Superior Dynamic Channel Selection and Handover procedures of DECT have proven to be efficient and reliable for large office and industrial installations both indoor and outdoor with 4000 to 5000 users per installation.

3.4 Research Projects

Several European, American and national projects are dealing with cognitive radio and Dynamic Spectrum Access. There are three main view angles : regulation, economy and technology. We review in this section the most important ones focusing on the technical aspects.

3.4.1 DARPA XG Program

The DARPA Next Generation Communications program is a project of the US department of defense. Its aim is to help the US army to efficiently use the available spectrum on any operation theatre, possibly in coordination with allied forces and the national spectrum planning. The project focuses on the definition of new waveforms, medium access and control technologies to build an integrated system [13].

According to [13], “the proposed program goals are to develop, integrate, and evaluate the technology to enable equipment to automatically select spectrum and operating modes to both minimize disruption of existing users, and to ensure operation of U.S. systems”. Materials [14-16] can be found at [17].

The motivation of the project is based on the observation that spectrum is scarce and that network deployments are difficult because there are many regulatory and policy rules (depending on the system, the frequency, the country, the region, etc). XG focuses on **Opportunistic Spectrum Access** and so adopts an approach where static spectrum allotment to primary users is complemented by an opportunistic use by secondary users. On top of a more efficient spectrum usage, OSA is supposed to provide easier deployment and rapid entry into regions where spectrum has been assigned [15].

The originality of the project consists in the definition of a ***policy agility***. As the management of the spectrum is now placed in each radio, these ones have of course to show ***spectrum agility***: they must be able to sense the environment, identify opportunities, coordinate, etc. But they also should be able to load on the fly machine understandable policies that are likely to change over time and geography. So one of the main tasks of XG is to define a policy language framework. The project aims also at defining generic behaviors and protocols for radio devices (the difference between behavior and protocol is related to the degree of abstraction but remains quite subtle). The generic process for transmitting data is shown on the following figure [18]:

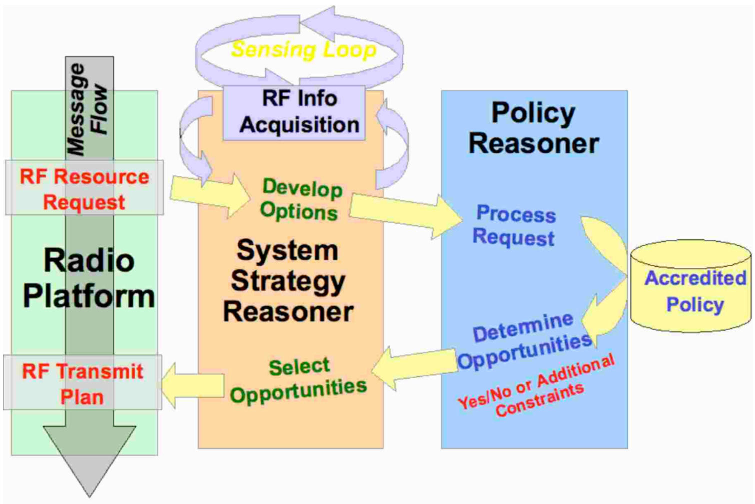


Figure 3.8 DARPA XG Operation (taken from [18]).

Besides the presented objectives and framework, few technical documents are available on the project. Reference [14] provides however some few hints about the solution at the MAC layer. The following figure shows where the XG MAC should be placed in the protocol stack. The XG processes at MAC and PHY layers are supposed to exchange spectrum occupancy information thanks to three modules [14]:

- The **opportunity awareness** module: responsible for the sensing of spectrum opportunities, the identification of usable opportunities and their associated constraints and the dissemination of this information in the neighborhood.
- The **opportunity allocation** module: responsible for allocating in a distributed manner the available opportunities for transmissions among the XG nodes.
- The **opportunity use** module: responsible in the PHY layer for the transmission of packets over the set of allowed opportunities.

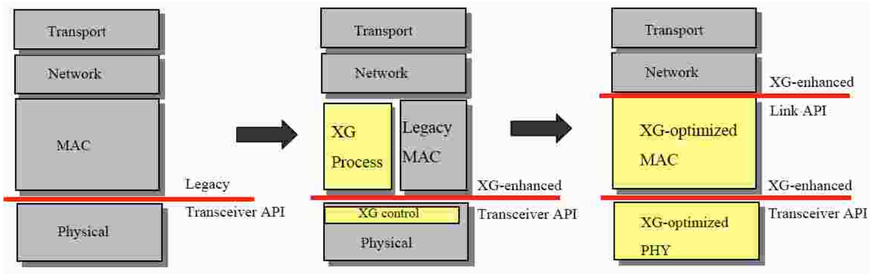


Figure 3.9 Evolution from legacy MAC, through coexisiting solution, to XG MAC [14].

Besides these generic concepts, practical examples are often based on listen-before-talk mechanisms and on RTS/CTS/DATA/ACK exchanges.

3.4.2 IST DRIVE and OverDRIVE Projects

One of the goal of the IST DRIVE project was to develop dynamic frequency allocation methods to allow the coexistence of different standard in the same frequency band and so reach a more efficient use of the spectrum. The basic idea is to exploit the time-varying traffic patterns of different services in order to increase spectrum utilization. The proposed study case considers spectrum sharing between UMTS and DVB-T. The **DSA algorithm** allocates frequency carriers according to the traffic load of each technology, as illustrated on the following figure:

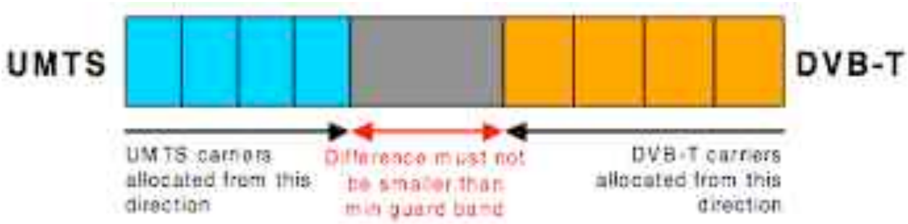


Figure 3.10 Dynamic allocation of spectrum in DRIVE [19].

Reference [19] describes the DSA algorithm. A prediction methods is proposed for traffic load estimation. Several priority schemes are proposed. Simulations are performed with the following performance metric: the satisfaction ratio defined as the ratio of the number of served calls to the number of required calls.

DRIVE has developed an architecture for hybrid systems and multi-RAN connectivity. In the **DRIVE architecture**, an entity, called the Traffic Control, has the responsibility to assist the terminal to select the most appropriate RAT and routes its traffic according to the selection. Information exchange and signaling between Traffic Control and DSA is done through a specific channel called the Common Co-ordination Channel (CCC). The architecture has a Spectrum Allocation Node function and a Traffic Management Node function. The latter estimates and predicts the traffic load, while the former determines how much spectrum is needed to serve the demand.

While in DRIVE, only contiguous DSA is considered (contiguous blocks of spectrum are allocated to the different RATs), Over DRIVE studies the so called flexible **fragmented DSA** (see next figure, any RAT can be assigned any piece of spectrum in a spectrum pool). DRIVE was only considering temporal DSA, while Over DRIVE has studied also **spatial DSA** [20] and the proposed algorithms exploit geographical spectrum usage differences.

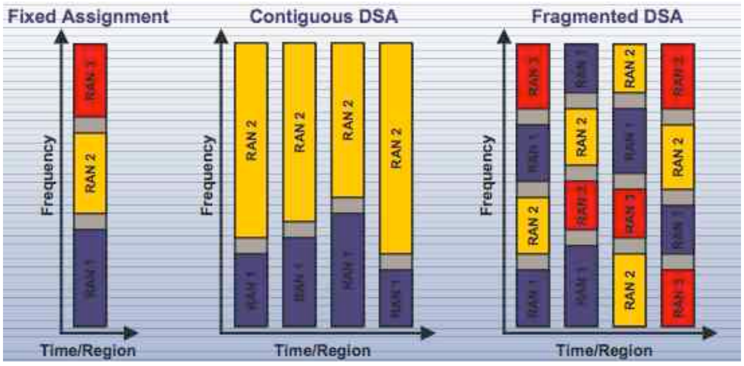


Figure 3.11 Fixed, contiguous and fragmented DSA according to DRIVE [21].

3.4.3 IST E2R Project

The End-to-End Reconfigurability (E2R) project proposes three mechanisms in [22] for a better spectrum usage. The first algorithm extends the concept of dynamic channel assignment to support inter-BS spectrum sharing for FDMA based systems. The algorithm is called eDCA. Reference [22] then discusses how WLAN system operations could be improved in a cognitive radio context to deal with spatial unfairness (in fact the document proposes a simple power control algorithm). At last, an interesting part focus on secondary markets.

According to [22] the **eDCA** principle is the following:

- Frequency carriers are pooled and can be accessed by any technology provided that the co-channel intra and inter RAT reuse distance is not violated. A frequency is said to be eligible for a new call if the frequency reuse constraints are satisfied for it.
- Frequency carriers are shared on a cell-by-cell basis and on a call-by-call basis (the mechanism is thus a kind of call admission control) in order to adapt to temporal and spatial variations of the traffic.

Performance evaluation is done with the queuing theory formalism by considering a linear cellular topology. The main drawback of this approach is the fact that the reuse distance are supposed to be perfectly known.

The last part of [22] focus on technico-economical aspects. A spectrum manager implements DSA by **auctioning short-term spectrum licenses**. At each start of a DSA period, operators bids for spectrum according to their demand and so the revenue they can expect from this spectrum. The auction format is the called the multi-unit Vickrey auction (see [23] for more details): this is a set of rules specifying how operators can bid for 1, 2,...,K elementary sub-bands and how much they have to pay if they win.

How much an operator can win from a spectrum band is given by its **pricing policy** (each terminal is charged per unit of allocated downlink power) and **terminals behavior** (they try to maximize a “benefits minus cost” utility function, which depends on the received SINR and on the price). So terminals maximize their utility, the operator deduce from the chosen powers the revenue that it can expect from a spectrum band and bids for it. If the amount of power is limited, the operator can also implement a service priority scheme. Authors extend this approach to a **two-RAT scenario** (DVB-T and CDMA networks), see [24] for more details.

3.4.4 IST WINNER Project

The IST WINNER project aims at defining requirements and solutions for B3G systems. In particular, new techniques are proposed to reach higher data rates. As higher data rates means translate immediately in larger spectrum demand, flexible use of the spectrum and spectrum sharing are seen as key features of B3G systems.

In [25][26], an architecture for spectrum sharing is proposed: needed functionalities and logical entities that implement these functionalities are defined. This is shown on the following figure:

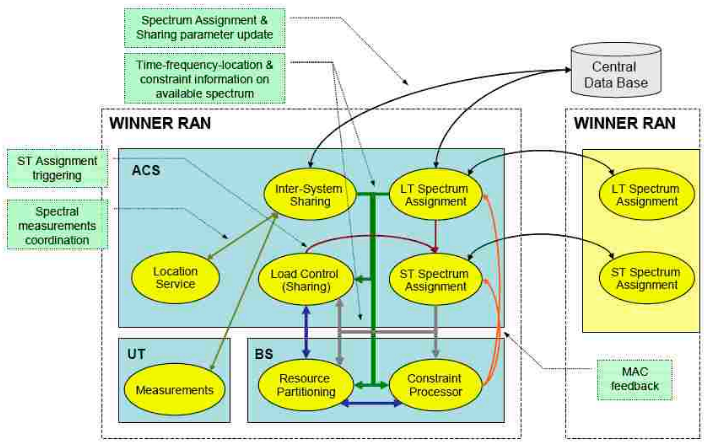


Figure 3.12 Radio Resource Management architecture in WINNER [26].

Reference [25] describes in details sub-functionalities and signaling messages between the logical entities. In [26], a simple assessment model shows the benefit that can be obtained from spectrum sharing. In the considered scenario, three different RAN share a pool of resources. Request are generated according to a given profile over a day time. Few simulations show the interest of sharing resources compared to the fixed assignment scheme.

3.4.5 WAPECS

In November 2005 the Radio Spectrum Policy Group (RSPG) has published an opinion on Wireless Access Policy for Electronic Communication Services (WAPECS). WAPECS is an approach to more flexible spectrum management and proposes a framework for the provision of electronic communications services within a set of frequency bands in which a range of electronic communications networks and services may be offered on a technology neutral and services neutral basis. The frequency bands which are appropriate for WAPECS are to be identified and agreed on between European Union Member States.

The RSPG consulted Member States to identify the relevant frequency bands for WAPECS, the range of licensing approaches which have or could be used, the rights that have been applied, the obligations that have been applied and some spectrum related challenges. According to the consultation of the Member States there is a wide range of frequency bands which could be used for WAPECS. The identification of frequency bands for WAPECS is not intended to be exclusive, or to imply that other bands cannot or should not also be used for WAPECS. The following bands are being discussed in the context of WAPECS:

Frequency band	Currently used terms for allocations and applications
174 – 230 MHz 470 – 862 MHz 1452 – 1479.5 MHz	Broadcasting (T-DAB and DVB-T)
1375 – 1400 MHz, 1492 – 1517 MHz, 1427 – 1452 MHz, 1350 – 1375 MHz and 3600 – 4200 MHz	Fixed bands (fixed Point-to-point below 6 GHz)
3400 – 3800 MHz, 24.5 – 26.5 GHz	Fixed bands (point-to-multipoint)
380 - 400 MHz, 410 - 430 MHz, 450 - 470 MHz, 870 - 876 MHz, 880 - 921 MHz, 925 - 960 MHz, 1710 - 1785 MHz, 1805 - 1880 MHz, 1900 - 1980 MHz, 2010 - 2025 MHz, 2110 - 2170 MHz and 2500-2690 MHz	Mobile bands
1880 - 1900 MHz (DECT) 2400 – 2483.5 MHz (RLANs) 5150 - 5350 MHz (RLANs) 5470 - 5725 MHz (RLANs)	Short Range Devices

Table 5.1 – Frequency bands considered by WAPECS[2]

A number of constraints have been identified, which have the potential to limit the use of particular bands for WAPECS and which in consequence pose challenges to the Member States in the future approach to spectrum management:

- **Legacy issues** arising from the initial assignment of individual rights to use frequencies. Spectrum has not always been assigned by the same allocation methods so that there are differing economic values of the different frequency bands and categories of networks used to deliver electronic communication services.
- As a result of regional and international agreements there is a **lack of flexibility** in some existing licences. Additionally, the long licence duration in some cases could make it difficult to change the rules quickly. Further, in the case of frequency bands harmonized at EU level, the transfer of rights of use shall not result in change of use of the harmonised radio frequency.
- **Licences or rights of use** may prescribe very specific technology or technical conditions to be used in a particular band. This can result in the inefficient use of spectrum or hamper innovation if the above mentioned licence conditions cannot be broadened or made more flexible in order to accommodate other technologies.
- The Member States may have to fulfil some **obligations relating to the use of the bands by particular services** pursuing particular general interest objectives, even when they fall under the WAPECS scope, and to safeguard some spectrum for them.
- **Technical conditions** are required to ensure the protection of bands used by other applications which are not electronic communications services (e.g. governmental).

WAPECS is targeted at introducing technology and service neutrality. Although the introduction of flexibility is an important objective it also is important to take into account the negative impact flexibility can have on harmonisation, on the development of equipment and networks (e.g. if the standardisation process fails), spectrum efficiency and protection against harmful interference as well as existing applications and technologies. Moreover, in the last debates, the WAPECS concept seems to need further specifications and will have to be adapted and introduced progressively in order to take into account legacy issues and present situations. It should be noted that the frequency bands identified for WAPECS include licensed as

[2] It has been proposed since then that 1800-1805 should be added to the list of bands to be addressed. This was done, along with a note explaining that this band should only be addressed by CEPT under WAPECS if it had sufficient time.

well as licence-exempt spectrum. Consequently, WAPECS would not hinder the development of the technologies considered in the SPORTVIEWS study as it would not prevent the allocation of frequency bands for spectrum sharing.

3.4.6 SPORTVIEWS

SPORTVEWS means "Spectrum Policies and Radio Technologies Viable In Emerging Wireless Societies". This project aims to analyse how the new wireless technologies can provide or require new methods of spectrum management, exploring the relations between advanced technologies, future services, industry structures and spectrum management methods in light of the objectives of the European Commission for harmonisation.

Information presented below comes from [51].

3.4.6.1 Technological innovation for spectrum management

UWB and low power devices

Ultra Wide Band was developed to transfer large data over short distances. To do this, UWB use a large spectrum band with low power devices to mitigate interferences. The use of low power devices generally is based on the use of licence exempt spectrum and therefore also means a reduction of administrative spectrum management methods.

Software defined and cognitive radios

SDR (Software defined radio) becomes interesting for the introduction of flexible spectrum management when it is employed as an enabler for cognitive radios. In this context it poses a challenge to spectrum management as cognitive radios are expected to identify unused or under-used spectrum and to use this "free" spectrum without interfering with other (potential or primary) users. This form of overlay spectrum sharing puts a different challenge to spectrum management.

Mesh network

Mesh networks offer new possibilities in wireless communications that may lead to additional spectrum requirements on a licence exempt basis. Therefore, mesh networking may require the identification of additional frequency bands for spectrum sharing. The total spectrum requirements depend on whether the applications of mesh networking require separate spectrum allocations or whether the devices are compatible and can coexist.

These new technologies need a new concept of spectrum allocation. The traditional spectrum management divide the spectrum among different uses and users, but a new approach was born with unlicensed use.

3.4.6.2 Collective use of spectrum

There are many approaches of collective use of spectrum. Each of them has its own merits depending on the applications that are expected to use the spectrum in particular, the required quality of service and the likely interference environment. Eight categories of collective use have been identified.

Licence-Exempt (commons) – non-specific applications

No individual authorisation or coordination is required and no fee payable for using the spectrum. Access is regulated solely by adherence to pre-defined regulatory conditions. Any application is permitted so long as the regulatory conditions are adhered to, which are typically low power, short range devices and applications.

Licence-Exempt (commons) – specific applications

No individual authorisation or coordination is required and no fee payable for using the spectrum. The equipment must comply with specific standard(s), either harmonised standards or national interface standards which relate to specific applications that are typically low power short range devices.

Light licensing – few restrictions

Registration or notification is required. There are no limits on the number of users but use may be application-specific. Typically, light licensing permits greater power than licence-exempt bands. A small fee may be payable to cover the costs of the registration / notification scheme. Light licensing is typically applied in situations where there is no immediate concern about interference but where there may be a need to make changes to the use of the spectrum in future, hence there is a need to maintain a record of those who are using the spectrum. For example, some European countries allow the use of the 5.8 GHz band for fixed wireless access services on a light licensing basis without the need to apply for an exclusive licence or right of use.

Light licensing – with restrictions

Registration or notification is required, and there are limits on the number of users and/or requirements for co-ordination between users. Use may be application-specific and typically permits greater power than licence-exempt bands. A small fee may be payable to cover the costs of the registration/notification scheme. Recent examples include:

1) a registration scheme proposed in the U.S for use of the 3650 – 3700MHz band on a collective basis for fixed wireless access where the risk of interference is mitigated by technical means, and where licensees are mutually obliged “to cooperate and avoid harmful interference to one another”;

2) the UK regulator Ofcom recently awarded through auction, twelve low power concurrent rights of use through auction for the frequencies 1781.7-1785MHz paired with 1876.7-1880MHz. Licensees are expected to co-ordinate their use of the spectrum to avoid harmful interference.

Private Commons

An individual right of use is required but access to spectrum may be “sublet” to third parties on an unlicensed basis without the need for co-ordination, so long as predefined regulatory conditions are adhered to. Responsibility for avoiding interference with users outside the spectrum band rests with the right of use holder. In the U.S., the Federal Communications Commission (FCC) recently introduced rules permitting spectrum leasing under which a licensee may acquire a block of spectrum to create a private commons for use by thousands or even millions of new users. The FCC speculated that this type of private commons could be used by innovative equipment vendors to roll out a new service such as a private Wi-Fi business. This could offer a higher quality of services than Wi-Fi and other users must now accept in existing licence-exempt bands.

Experimental Commons

Experimental licences are intended for use on an experimental basis for some predefined and limited period of time. Licensing, registration or notification is dependent on the specific allocation, but there are generally no limits on the number of users, and there may be no restriction on the application. Operation is on a non-interference, non protected basis, and operational constraints may apply (e.g. prohibition on provision of third party services). Technical constraints may apply generally or may be specifically negotiated. A small fee may be payable to cover the costs of the registration/notification scheme.

Underlay

Underlay technologies operate in spectrum that is used for other licensed or licence-exempt use but at very low power levels. This allows the underlay use to share or collectively use the spectrum. Underlay use is not licensed. Ultra Wide Band (UWB) is an example of an underlay technology.

Overlay

An overlay approach permits higher powers that could cause interference to existing users, but overcomes this risk by only permitting transmissions at times or locations where the spectrum is not currently in use. This can be achieved either using technology (e.g. cognitive radio) or by regulatory means (e.g. only permitting use in certain geographic regions). Here we are concerned with overlay use that is not licensed.

The following hierarchy can be defined in terms of the level of protection that a user can expect:

- Full protection: Exclusive right of use required; provides legal recourse in the event of harmful interference.
- Partial protection: Collective use, restricted to specific applications and/or technologies; no legal recourse against interference from other legitimate spectrum users.
- No protection: Collective use, open to all applications and technologies subject to compliance with certain technical parameters; no legal recourse against interference from other legitimate spectrum users.

3.4.6.3 New Technologies and Spectrum Pricing

The new technologies studied by the SPORT VIEWS project could have a significant impact on spectrum prices and pricing methods. On the one hand, as far as UWB, software defined radios, cognitive radios and other new technologies penetrate the market, they are expected to help increase spectrum use (provided that they do not introduce costs such as higher interference levels) and enhance spectrum access, thereby providing a means to reduce artificial spectrum scarcity. Other things being equal, the price of such spectral resources can be expected to decrease. On the other hand, new applications and new services might be developed building on the capabilities of new technologies and an increase in the (derived) demand for spectrum may follow. However, there is a belief that, at least in the short run, the deployment of new technologies will not cause (or exacerbate) spectrum scarcity.

3.4.6.4 Strategy/future approach of national regulators

The interviews of national regulators have shown that there are common and different views on how to approach spectrum management issues. Given that spectrum management also is determined by international decisions and agreements, the future approach of national regulators will strongly depend on the outcome of the WRC 2007 and the decisions of the European Commission on spectrum management issues. It is to be expected that decisions on technological and services flexibility will be greatly influenced by the development of WAPECS at European level.

Within the limits of the international and European framework, each regulator will then decide on the role the various flexibility spectrum management tools will play at national level. These decisions will reflect the different views of regulators on the right approach to spectrum management in a sense that some will have a strong interest in promoting market or competitive mechanisms and in allowing for the easements within property rights, versus those regulators preferring a conservative approach.

3.4.7 SDR Forum

The main source of this section is the SDR Forum WebSite.

The Software Defined Radio Forum (SDRF) is a non-profit organization comprised of approximately 100 corporations from around the globe dedicated to promoting the development, deployment and use of software defined radio technologies for advanced wireless systems. Forum members are decision makers, planners, policy makers and program/product managers from a broad range of organizations sharing a common view of advanced wireless networking systems evolution.

SDR concepts form the building blocks to integrate applications over any air interface at any point in time.

These building blocks are implemented as adaptable software and flexible open hardware platforms to address the interoperability issues arising from the constant services evolution and technical innovation that defines the wireless industry. SDR is an emerging technology that spans all radio network topologies in the commercial, military and civil government sectors, and enables highly flexible solutions with benefits to operators, manufacturers and consumers.

SDR technologies provide software control of a variety of modulation, interference management and capacity enhancement techniques over a broad frequency spectrum (wide and narrow band), while ensuring secure communications management. Radios built using SDR concepts offer:

- Standard architecture for a wide range of communications products
- Non-restrictive wireless roaming for consumers by extending the capabilities of current and emerging commercial air-interface standards
- Uniform communication across commercial, civil, federal and military organizations
- Flexibility and adaptability
- Potential for significant life-cycle cost reductions
- Over the air downloads of new features and services as well as software patches
- Advanced networking capabilities to allow truly "portable" networks
- Worldwide interest and investment in the SDR technologies is growing significantly, with key standardization and development efforts now taking place throughout Europe, North America, Japan, Korea, and China.
- In addition to the broad benefits listed above, SDR technologies offer unique benefits to players on every tier of the value chain.

Technical committee and work groups are organised as follows. This organisation and its themes shows which are the subject of interests according to the SDR Forum.

Cognitive Radio: Cognitive Radio is the next major challenge, putting the smarts of the software in SDR radios to work to optimize the radios, their spectrum use, the networks that connect the radios, and provide the users with services to help them in their daily activities. While much development has gone into design of network protocols, the sophistication to be able to find and utilize unused spectrum without interfering with existing radios has the potential to significantly expand telecommunication services, and magnify what is already a $1T/year market. The Cognitive Radio Work Group is working to define the use cases for cognitive radios. This effort will lead to the development of a cognitive radio functional specification that is a platform independent model specification. They have also established liaison with other organizations also working in related topics such as ITU, IEEE P1900, and E2R. Through these relationships, we will be able to harmonize documents and language so that international standards will have improved commonality.

Commercial: The commercial work group has been doing investigative work that will lead to the development of a meta-language standard for commercial cognitive radio applications. This will enable cognitive radio standards assisting with automated SDR software installation, compatibility, and maintenance. Of particular importance is establishment of a commercially acceptable language for specification of Policy for Policy defined and cognitive radios. It will also make interoperable standards for cognitive radios a near term possibility. This is new technical effort for the SDR Forum and the work group is soliciting companies to participate with them in this development of a meta-language standard.

Design Processes and Tools: The objective of the Design Process and Tools Working Group is to improve productivity and quality in the development and deployment of software defined radio technology through enhancement of the tools used by the industry. To achieve this end, the DPT-WG will make SDR Forum recommendations on the best practices for design flows and tools used by industry in creating systems, software, waveforms, and components.

Education: The industry needs engineers trained in SDR technologies. SDR Forum established the Educational Work Group to provide a way for leadership faculty to get together and discuss curriculum and training delivery topics, and to prioritize the development. The group is also seeking to enroll participation of various branches of the government such as NSF, DARPA, and Congressional support.

Research and Development: Identify and describe technologies and development topics, significant for SDR in terms of need, technological challenge and maturity by creating Technical White Papers, Recommendations, Summary Reports and organizing Expert Briefings, and advancing those technologies in the industry.

SCA : The SCA Working Group is chartered with facilitating the structural harmonization of the SCA and its elements with other associated standards, helping the industry converge on a consolidated set of solutions.. Current topics include scalability, standardized APIs, and Global testing.

SDR Security: The SDR Security Working Group is focused on a broad set of security issues that arise from the introduction of SDR technology. The Working Group seeks to produce a security framework that could be applied to any use of SDR, not favoring any current market segment of radio technology (e.g., commercial wireless telephony).

Smart Antenna : Smart Antenna WG is working on a set of standardized APIs to support smart antenna technology such as beam-forming algorithms, nulling, adaptive antennas, DSP/FPGA techniques, network interface, SA base station architecture, standards of various applications, etc. Recently discussions in SA WG focus on multiple mode SA architecture to support SA systems operating in SDR networks.

Space: The objectives of the SWG are to develop an open SDR hardware and software architecture suitable for the resource constrained, space domain and provide recommendation for the Space Communications Architecture Working Group. The architecture shall provide a consistent and extensible development environment on which to construct and operate space applications.

System Interface : SIWG is responsible for identifying radio, management, network, and physical services and their interfaces. SIWG maintains and promotes system interface standards and develops and promulgates new standards when necessary.

3.5 Scientific Literature

The scientific literature (besides traditional journals and conference in wireless networks, several conferences are dedicated to cognitive radio and dynamic spectrum access like IEEE DySPAN or SDR Forum) focuses on few themes (we exclude here surveys, signal processing, software define radio SDR, testbeds and measurements campaigns):

- Opportunistic Spectrum Access;
- Dynamic Operator Sharing;
- Commons;
- Definition of spectrum policies;
- Capacity limits of cognitive radio.

This section provides entry points for the scientific literature for each of these themes.

3.5.1 Opportunistic spectrum access

Opportunistic spectrum access refers to the case where a secondary user accesses the channel licensed to a primary user in an opportunistic way. This set of papers includes coexistence studies between existing systems. Several MAC protocols are proposed to facilitate the secondary access (through pilot channels, beacons for example). We shortly describe hereafter some important references on this topic.

Reference [12] lists **several issues to be solved**. At the physical layer [12] argues that OFDM is the most interesting modulation for the secondary user because it can easily adapt to the primary user transmissions by choosing the right sub-carriers. Among the listed challenges we can cite: the detection of the spectral access of primary users (often based on Neyman-Pearson criterion), the share of measurements between secondary terminals (the paper proposes a so called “boosting protocol” at the physical layer) and the mitigation of adjacent interference (if frequency bands are close). At the MAC layer, [12] describes a classical traffic model for primary users. It highlights the fact that a new kind of hand-over is needed between pools of sub-carriers if a primary user is suddenly transmitting on the current pool.

Many papers use the formalism of **game theory** to describe the opportunistic spectrum access scenario. Reference [38] is a good summary of models, challenges and works in this field (see references in the paper). Several models are interesting. The game can be non-cooperative (Nash equilibrium and Pareto optimality plays a significant role) or cooperative (the Nash bargaining solution is possible outcome of the game). In order to introduce dynamicity, multi-stage games can be introduced to take into account the fact that players take actions sequentially. When primary users attempt to sell unused spectrum to secondary users, while secondary users try to acquire resources, auction theory is the right framework.

Several papers focus on the so called **spectrum sensing problem**: in a cognitive radio architecture, secondary users have to detect as quickly as possible the presence of primary users with the highest possible detection probability and the lowest possible false alarm probability. Reference [39] is an example of reference in this domain that use an Amplify-and-Forward cooperative scheme to improve the detection agility.

Primary users can help secondary users to know when they are allowed to transmit. A possible implementation at the MAC layer is to introduce a **pilot channel, beacons or a common control channel**. Pilot channels usually broadcast either permissions (or grants) for secondary users to access the data channel or denials of access. Reference [42] is a good example of such a scheme.

3.5.2 Dynamic Operator Sharing

Dynamic exclusive use refers to the case where several (but few) operators or license owners share a spectrum band with equal rights. Relatively (compared to opportunistic spectrum access for example) few papers address this scenario. We have seen in a previous section that E2R project has considered the case of auction driven allocation [23][24].

In reference [49], a single operator is considered but spectrum is dynamically shared among base stations according to the traffic demand. In [50], coordinated DSA is considered between operators.

3.5.3 Commons

In the “commons” scenario, many users have to share a common spectrum band.

Reference [43] address the issue of designing spectrum sharing rules in the “commons” scenario, which lead to a Nash equilibrium that is fair and efficient. Authors first consider a static game of complete and perfect information, known as **Gaussian Interference Game** and show that the best possible strategy is to spread the available power over the total bandwidth. Then, they consider a infinite horizon repeated game, where the previous static game is repeated forever and deduce for some scenarios the regions of achievable rates.

Several papers address the issues induced by the **coexistence between systems**. For example [44] studies the coexistence between Bluetooth and WLAN and proposes to introduce a common spectrum control channel to facilitate spectrum sharing. A similar idea is proposed in [45] for the coexistence between WLAN and 802.16a networks. Paper [46] is at the cross-road between “opportunistic” and “commons” access since the spectrum sensing problem is studied for the coexistence between WLAN and Bluetooth. Reference [46] proposes a statistical characterization of the WLAN activity based on a continuous time Markov chain. Then a frequency hopping scheme is proposed for Bluetooth devices that exploit this prediction model to reduce the number of collisions with WLAN.

Reference [47] models the “commons” scenario with Markov chain and propose an fair and random **channel access protocol**. More original is the distributed version of this protocol. It is based on a Homo Egualis (HE) society model. Contrary to the classical “rational” and selfish behavior of users usually assumed in game theory, in a HE society, individuals have an inequality aversion. HE society can be modeled by choosing an utility function that takes into account fairness among users. The proposed protocol is said to achieve near-optimal results.

The **dynamic spectrum allocation problem** consists in allocating non-interfering time-frequency blocks to links with traffic demand. From this problem, we can derive a throughput maximization problem or a proportionally fair throughput maximization problem. This issue of channel assignment is the subject of several papers that rely on results on the graph-coloring problem and its variants. In [48] a centralized and a decentralized protocol are proposed for spectrum allocation. The Cognitive Radio MAC protocol is based on a three-handshake on a common control channel.

3.5.4 Spectrum policies

We have seen in a previous section that one of the aim the XG program was to define machine understandable policies. This is also the aim of paper [37] which defines a new language for expressing policies that allow opportunistic spectrum access.

3.5.5 Capacity limits of cognitive radio

Several papers have a information theoretic approach of cognitive radio and aim at finding the capacity limits / achievable rates of a cognitive radio channel. We shortly describe hereafter two sets of papers on this topic.

Reference [33] proposes several simplified models for studying a channel where a secondary user and a primary user share the same band: 1) the “known interference” model (secondary user has a priori knowledge of the primary users transmissions and of the channel gains); 2) the “interference avoidance” model with two sub-models 2a) the “two-switch” model (secondary transmitter and receiver can communicate iff none of them detects the transmission of a primary user) and 2b) the “opportunistic channel selection” model (secondary transmitter and receiver use frequency hopping or tracking to avoid interfering a primary user). Reference [34] studies in more details the **“two-switch” model** and derive capacity expressions for several sets of assumptions concerning available activity information.

Reference [36] defines **the cognitive radio channel** as follows: this a 2 transmitter, 2 receiver interference channel in which sender 2 (a cognitive radio) obtains, or is given by a genie, the message sender 1 plans to transmit. This is illustrated on the following figure:

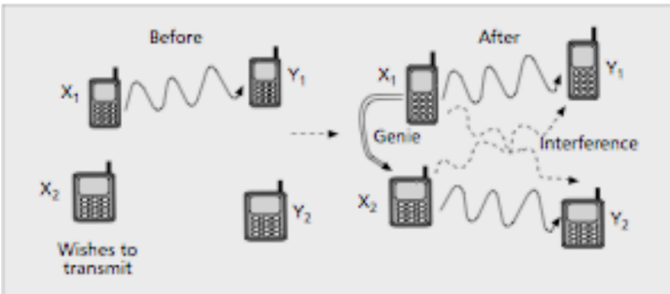


Figure 13 Cognitive Radio Channel according to [36].

For this kind of channel, authors derive in a set of papers (see e.g. [35]) the achievable capacity region by using the dirty paper coding.

4 Conclusion

This document provides an extensive survey on the topic of dynamic spectrum management. Dynamic spectrum access is a huge and hot topic that embraces many research areas. Moreover, as the topic is really emerging since few years, the vocabulary is not so stable. That is the reason why the document starts by providing a classification of the models and paradigms used in this field. This classification intended to trade-off between simplicity (few big classes are highlighted) and completeness (almost all DSA algorithm can be classified).

The third party of the document gives an extensive state of the art in the domain: from regulation to scientific literature, going through existing systems and research projects. It is shown that many tools and mechanisms already exist to enable dynamic spectrum access and that many studies have been performed in the past, especially on the coexistence between standardized systems.

In terms of research prject, URC is the follower of several programs. The first one was probably XG DARPA (1999) but several IST projects have investigated these issues: DRIVE, OverDRIVE, WINNER I and WINNER II, E2R. These projects have provided generic architectures and DSA algorithms.

This document shows also that the standardization bodies are very active in the field, especially IEEE with P1900, 802.22 and 802.16.

5 Appendix on existing systems: networks operated by SNCF

Ce document représente un livrable de la contribution de la SNCF au SP1 du projet « Urbanisme des RadioCommunications ». Il fait un état des moyens de radiocommunications exploités aujourd'hui dans l'entreprise tant du point de vue des fréquences que de celui des types de réseaux.

5.1 Préambule

Il n'est traité ici que des applications utilisées par la SNCF pour ses propres besoins de transporteur ferroviaire (gestion, entretien et sécurité). Il n'est pris en compte que les réseaux radioélectriques exploitant des fréquences assignées. En effet du fait de la centralisation des affectations de fréquences ces réseaux sont connus du Département des Télécommunications ce qui n'est pas le cas des réseaux réalisé, sur des initiatives locales, avec du matériel utilisant des fréquences de plein droit.

5.2 Réglementation

5.2.1 Généralités

Les réseaux de la SNCF dépendent de l'article L33-2 du code des Postes et des communications électroniques, c'est-à-dire des réseaux indépendants à usage privé et professionnel.

5.2.2 Bandes concernées

La SNCF, et RFF, ne sont pas directement des attributaires de fréquences. Dans ce domaine, ils dépendent de l'ARCEP. Pour satisfaire les besoins du transport ferroviaire, cet organisme affecte en majorité ses propres canaux. Mais pour des besoins particuliers, elle joue le rôle d'intermédiaire vis-à-vis d'autres attributaires. Il s'agit principalement :

5.2.2.1 Des Forces Armées (BMNF)

Qui ont attribués dix couples de la bande 424 / 414 MHz pour le réseau IRIS*, à la norme TETRAPOL, dédié à la sécurité des biens et des personnes en Ile-de-France.

5.2.2.2 De l'audiovisuel (CSA)

Qui met à disposition de la SNCF, trois canaux de la bande 50 - 65 MHz en Ile-de-France pour l'application de télévision semie-embarquée TVSE*.

5.2.3 Grand Compte SNCF

Si la SNCF n'est pas un attributaire, elle est quand même un grand utilisateur de moyens radioélectriques. A titre d'information il existe, sur l'ensemble de la France, environ 2 000 réseaux élémentaires qui vont du réseau local de quelques portatifs au réseau régional de plus de cent stations relais interconnectés par câble le long des voies. Le parc est supérieur à 30 000 terminaux radio. En effet bien qu'exploités uniquement pour ses propres besoins de transporteur ferroviaire ils couvrent des domaines aussi variés que la gestion, l'entretien, l'information ou la sécurité des biens et des personnes.

De par cette position la SNCF possède depuis 1997 des fréquences exclusives reprises dans un « Grand Compte SNCF » ou « 3 Bis » en référence à l'article 3 Bis du décret du 3 février 1993 relatif aux redevances de mise à disposition de fréquences radioélectriques et de gestion dues par les utilisateurs d'autorisations.

Par ce texte une certaine flexibilité est accordée aux attributions de la SNCF. Ces caractéristiques sont les suivantes :

Non transférable

L'autorisation est attribuée à la SNCF, mais celle-ci peut accueillir des utilisateurs tiers identifiés qui participent à l'exploitation du réseau ferroviaire.

Usage exclusif

Suivant les sous bandes de fréquences, elles sont exclusives :

sur l'ensemble de la France, avec éventuellement des contraintes à la frontière de certains pays.

le long des emprises ferroviaires nationale, avec éventuellement des contraintes à la frontière de certains pays.

en Ile-de-France.

Règles

Limitées à l'espacements entre canaux suivant les bandes, à la puissance, à la technologie analogique et au respect des règles de l'art.

Long terme

Suivant les sous bandes de fréquences, elles sont autorisées pour une durée de sept ou quinze ans. La fin du Grand Compte SNCF actuel est fixée à janvier 2012.

Centralisé

Le Département des Télécommunications de la SNCF est l'interlocuteur unique de l'ARCEP et de l'ANFR. Il gère l'ensemble des autorisations à l'aide d'une base de données informatique, effectue les attributions de fréquences à l'aide d'un logiciel de prédictions radioélectriques, édite les documents administratifs d'autorisation et s'assure du paiement des redevances.

5.2.4 Hors Grand Compte SNCF

Pour des applications particulières la SNCF à besoin d'exploiter d'autres canaux non repris dans le Grand Compte. Il s'agit de fréquences supplémentaires dans les zones denses du point de vue radioélectrique, d'expérimentation de nouvelles applications ou d'utilisation de technologies ne fonctionnant pas dans les bandes du Grand Compte.

Ces attributions sont traitées par L'ARCEP, sur présentation d'une demande écrite, suivant les procédures classiques de la PMR.

5.3 Systèmes actuels

5.3.1 Rappel

Les technologies et les principales caractéristiques techniques exploitées par les différentes applications de la SNCF ont été décrites dans l'annexe 3 du livrable du SP1 D1.1.1

5.3.2 Technologies

5.3.2.1 Analogique

Aujourd'hui la majorité des réseaux en exploitation à la SNCF sont de type PMR analogique. Il n'y a pas d'allocation dynamique du spectre. Le principe d'attribution est la réservation d'une fréquence par application (groupe d'utilisateurs).

Les fréquences sont attribuées par l'ARCEP ou le Département des Télécommunications de la SNCF (respectivement pour le Hors Grand Compte ou pour le Grand Compte SNCF).

Les études sont effectuées réseau par réseau, à l'aide d'outils informatiques, en fonction du type d'installation choisie, de la zone d'évolution de l'application ainsi que des autres réseaux SNCF se trouvant à proximité. Les règles utilisées lors de l'attribution de fréquences tiennent compte des problèmes de réutilisation du canal, de l'utilisation des canaux adjacents, de l'intermodulation de la forme 2F1-F2=F3 et de l'harmonique trois (utilisation sur un même site de canaux des bandes 152 MHz et 457 MHz).

5.3.2.2 Numérique

En technologie numérique seul le réseau IRIS* est déployé actuellement (203 stations sur l'Ile-de-France). L'installation du GSM-R* et des réseaux à la norme TETRA vient à peine de commencer. Ces applications sont destinées à remplacer et à mutualiser les anciens réseaux analogiques.

Pour les réseaux TETRA le dimensionnement est déterminé par la SNCF, le matériel est de type standard choisi dans le catalogue des fournisseurs et l'attribution des canaux est réalisée par l'ARCEP sur présentation d'un dossier.

Pour le réseaux IRIS* à la norme TETRAPOL, chaque site est équipé de deux canaux 12.5 KHz (une voie de signalisation et une voie de trafic). Du fait du faible trafic de ce réseau et de l'obligation de couvrir l'ensemble des lignes de la banlieue Parisienne, des cellules « iso fréquence » de plusieurs sites adjacents ont été créées. IRIS* autorise des liaisons en mode réseau, en mode relayé ou en mode direct. Les systèmes TETRA et TETRAPOL sont relativement proches en ce qui concerne l'architecture du système et les services offerts aux utilisateurs. La différence majeure est le niveau renforcé de sécurisation des transmissions dans la norme TETRAPOL. Les principales caractéristiques se retrouvent sur le site : http://www.tetrapol.com

Le GSM-R* reprend les principales caractéristiques du GSM public auquel il ajoute des fonctionnalités spécifiques :

La création de niveaux de priorité donnant la possibilité de préemption d'appel en cas d'urgence.

La transmission d'alerte (appel de groupe hautement prioritaire).

Le routage des appels en fonction de la localisation.

L'exploitation d'une numérotation fonctionnelle (par exemple le numéro du train) plutôt que le numéro d'abonné.

5.4 Coordination aux frontières

Les applications relatives à la sécurité des circulations (RST* analogique actuelle et futur GSM-R* numérique) sont européennes. Les bandes de fréquences sont harmonisées entre les pays et une répartition des canaux entre les différents réseaux a été faite au niveau des frontières. Les négociations entre les pays ont été effectuées par l'intermédiaire de l'ARCEP ou par l'autorité de l'époque pour la RST* analogique.

Quelques systèmes ne sont exploités qu'en région parisienne (IRIS*, TVSE* et BAM*).

L'ensemble des autres applications doit faire l'objet, au coup par coup, d'une coordination aux frontières. Celle-ci est menée par l'ANFR :

Pour les demandes du Grand Compte, la SNCF transmet à l'ANFR une grille reprenant les principales caractéristiques géographiques, structurelles, fréquentielle et techniques de l'installation projetée.

Pour le Hors Grand Compte c'est l'ANFR qui traite directement la coordination en fonction des informations qui apparaissent dans le dossier technique transmis lors de la demande de fréquence.

5.5 Qualité de service

Parmi les applications de la SNCF il est possible de déterminer plusieurs catégories, les applications :

Relatives à la sécurité des circulations (RST*, GSM-R* et commande de manoeuvre), des biens et des personnes (IRIS* et TVSE*) nécessitant une grande disponibilité.

De commodité dont la disponibilité demandée est moindre.

Afin de rester maître de la qualité de service des principales applications, de sécurité des circulations ou de la manœuvre des trains, celles-ci sont réalisées dans les bandes de fréquences du Grand Compte SNCF.

Note : (**BAM** - **IRIS** - **GSM-R** - **RST** - **TVSE** *) : La définition, la description, la structure et les caractéristiques techniques des différentes applications de la SNCF sont reprises dans le SP1 D1.1.

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7 Abbreviations

ACK: Acknowledgement

ANFR: Agence Nationale des Fréquences

ARCEP: Autorité de Régulation des Radiocommunications Electroniques et des Postes

Bluetooth SIG: Bluetooth Special Interest Group

BMNF: Bureau Militaire National des Fréquences

BRAN: Broadband Radio Access Networks

BS: Base Station

B3G: Beyond 3rd Generation

CDMA: Code Division Multiple Access

CIR: Carrier to Interference Ratio

CR: Cognitive Radio

CSA: Conseil Supérieur de l’Audiovisuel

CSMA/CA: Carrier Sense Multiple Access with Collision Avoidance

CTS: Clear To Send

DARPA: Defense Advanced Research Projects Agency

DCA: Dynamic Channel Access (or Dynamic Channel Assignment)

DCS: Digital Cellular System

DECT: Digital Enhanced Cordless Telephone

DFS: Dynamic Frequency Selection

DRIVE: Dynamic Radio for IP-Services in Vehicular Environments

DSA: Dynamic Spectrum Access

DVB-T: Digital Video Broadcasting Terrestrial

eDCA: Enhanced DCA

EIRP: Effective Isotropic Radiated Power

ETSI: European Telecommunications Standards Institute

E2R: End-to-End Reconfigurability

FCA: Fixed Channel Allocation (or Fixed Channel Assignment)

FCC: Federal Communications Commission

FDD: Frequency Division Duplex

FDMA: Frequency Division Multiple Access

GSM: Global System for Mobile Communications

HCA: Hybrid Channel Assignment

IEE: Institute of Electrical Electronics Engineers

ISM: Industrial, Scientific and Medical band

ISP: Internet Service Provider

ITU: International Telecommunication Union (http://www.ITU.org)

MAC: Medium Access Control

MC: Multi Carrier

OSA: Open Spectrum Access

PMR: Private Mobile Radio

PPDR : Public Protection and Disaster Relief

QoS: Quality of Service

RAN: Radio Access Network

RAT: Radio Access Technology

RFF: Réseau Ferré de France

RLAN: Radio Local Area Network

RTS: Ready To Send

SC: URC Scenario

SCO : Synchronous Connection Oriented

SINR: Signal to Interference plus Noise Ratio

SNCF: Société Nationale des Chemins de Fer

SP: Sous-Projet

TDD : Time Division Duplex

TDMA : Time Division Multiple Access

TETRA: Terrestrial Trunked Radio

TPC: Transmit Power Control

TH: URC transversal theme

UHF: Ultra High Frequency

UMTS: Universal Mobile Telecommunications System

US: United States

UWB: Ultra Wide Band

VHF: Very High Frequency

WG: Working Group

WiMAX: Worldwide Interoperability for Microwave Access

WLAN: Wireless Local Area Network

WPAN: Wireless Personal Area Network

WRAN: Wireless Regional Area Network