# Chapter 2
# Deployment Scenarios for Cognitive Radio

**Luca De Nardis and Oliver Holland**

**Abstract** This chapter presents a selection of potential deployment and application scenarios for Cognitive Radio (CR). The chapter goes beyond a simple review of scenarios by considering the viewpoints of several key players in wireless communication research and applications: regulators, standardisation bodies, researchers from the engineering and economic/business communities, industrial partners and companies. In this framework, two key issues related to scenario definition are addressed: (1) An analysis of players that determine the evolution of scenarios, including both technical and economic/business aspects; (2) Study of approaches for classification of CR deployment scenarios, with the aim of identifying a set of elements that allow creating taxonomy capable of fitting existing and new scenarios relevant to CR and SDR. The chapter opens with an overview of CR scenarios proposed by ITU-R in Sect. 2.1. It is followed by Sect. 2.2 that describes the CR use cases envisaged by ETSI. Section 2.3 offers examples of CR scenarios developed in several research projects. The impact of different regulatory and environmental conditions on application scenarios is addressed in Sect. 2.4, which provides a comparison between feasible scenarios in India and Finland. Section 2.5 highlights the issue of growing spectrum demand for mobile services and suggests how the CR may be positioned to help meeting that demand. This is followed up in Sect. 2.6 which provides analysis of upcoming mobile scenarios in Europe focusing on the concept of Licensed Shared Access as defined based on activities carried out in ETSI and CEPT. Next, the chapter moves on to aspects related to planning and classification of scenarios. Section 2.7 proposes a scenario planning methodology aiming to support planning and classification of scenarios for CR and to help identify relevant business models. Section 2.8

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proposes an approach to the definition of a taxonomy of CR application scenarios, aiming at fitting present and future applications in a coherent framework. Finally, Sect. 2.9 offers an example of very practical application scenario for deployment of White Space Devices in TV Bands as established by a harmonised European standard EN 301 598.

## 2.1 ITU-R Scenarios

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This section follows on the previous introduction of ITU-R activities in Sect. 1.1. It may be noted that ITU-R has published two reports on scenarios for Cognitive Radio Systems (CRS). One is about land mobile radio service [1], whereas the other is more specifically about International Mobile Telecommunications (IMT) systems [2]. In the case of land mobile service, a CRS may be implemented in frequency bands allocated exclusively to the mobile service or frequency bands that have multiple radiocommunication service allocations.

### *2.1.1 Land Mobile Radio Service*

The following scenarios for a CRS in the land mobile service have been identified in [1]:

- **Scenario 1: Reconfiguration of connections between terminals and radio systems** In this scenario, multiple radio systems employing different radio access technologies (RATs) are deployed on different frequency bands to provide wireless access. Reconfigurable terminals are able to dynamically adjust their operational parameters and protocols to use different RATs and to obtain knowledge required for these decisions. Alternatively, radio systems may assist terminals (e.g. using control channel). If terminals are able to communicate with other radio systems but not to reconfigure their parameters, additional multi-RAT nodes can be deployed to bridge these terminals to multiple radio systems;
- **Scenario 2: An operator improving the management of its spectrum** Exploiting CRS capabilities, a network operator managing two or more RATs can dynamically and jointly manage the resources of the deployed RATs, in order to adapt the network to the dynamic behaviour of the traffic and to globally maximize the capacity;
- **Scenario 3: An enabler of cooperative spectrum access** Using CRS technology, parts of the spectrum remaining unused due to variations in the

spectrum occupancy can be utilized. The capability to predict these variations or to exchange information on the spectrum usage among systems allows operators to agree on spectrum sharing and avoid mutual interference. Also cooperation between public land mobile networks and private networks can be considered;

- **Scenario 4: An enabler for opportunistic spectrum access** In this scenario, the CRS can access parts of unused spectrum in bands shared with other radio systems and services without causing harmful interference. This can be done by identifying the unused spectrum resulting from variations over time or geographic area e.g. based on a real-time radio environment analysis. The identified spectrum could then be used for different types of communication e.g. device-to-device communications. When the spectrum availability is more static e.g. TV white spaces, the CRS can locate and utilize the unused parts of the spectrum through its capabilities. Alternatively, CRS technology can enable multiple radio systems to share a band with equal access to it.

From the above scenarios, the first two scenarios are intra-system scenarios, allowing an operator to obtain more efficient use of its resources within the networks that it is managing. The latter two are inter-system scenarios, where CRS technology is used for providing more flexible use of spectrum between different operators or systems.

### 2.1.2 IMT Systems

IMT systems are operating in a globally harmonized and regulated spectrum bands as will be described in more detail in Sect. 2.5. The introduction of CRS capabilities and their applicability to IMT systems should be carefully evaluated. An IMT system employing CRS technology should still meet the minimum requirements for IMT systems [3] and it should not cause harmful interference or quality-of-service (QoS) degradation to the existing IMT systems. In the case of IMT, only intra-operator scenarios were identified in ITU-R [2], see also Fig. 2.1:

- **Scenario 1: Updating a network for optimized radio resource usage** A CRS management entity enables a mobile network operator (MNO) to manage radio resources more efficiently and optimize the network performance in terms of QoS. Load balancing can be done between different applications on a specified RAT or among different RATs when traffic varies from one area to the other depending on the time of day. This can be done autonomously e.g. based on measurements. Additionally, combined knowledge of the radio environment and geo-location information can be used for making optimal handover decisions for intra- or inter-RAT and intra- or inter-frequency band handovers;
- **Scenario 2: Upgrading an existing radio interface or a network with a new radio interface** An MNO of a RAT can decide to deploy a new RAT in the same frequency band to eventually replace the first one and provide all mobile services. During a transition period the legacy mobile devices, that only have
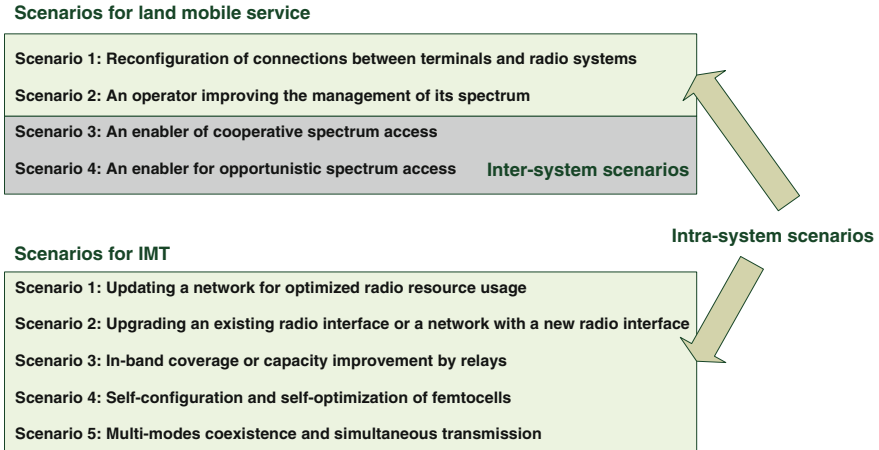
**Scenarios for land mobile service**

| |
|---|
| Scenario 1: Reconfiguration of connections between terminals and radio systems |
| Scenario 2: An operator improving the management of its spectrum |
| Scenario 3: An enabler of cooperative spectrum access |
| Scenario 4: An enabler for opportunistic spectrum access    **Inter-system scenarios** |

**Intra-system scenarios**

**Scenarios for IMT**

| |
|---|
| Scenario 1: Updating a network for optimized radio resource usage |
| Scenario 2: Upgrading an existing radio interface or a network with a new radio interface |
| Scenario 3: In-band coverage or capacity improvement by relays |
| Scenario 4: Self-configuration and self-optimization of femtocells |
| Scenario 5: Multi-modes coexistence and simultaneous transmission |

**Fig. 2.1** CRS scenarios from ITU-R in [1] and [2]

access to the first technology, coexist with multi-mode mobile devices accessing both technologies. To guarantee QoS during this period, reconfigurable base stations (RBSs) together with appropriate mechanisms are needed to manage the radio resources. Using CRS technology, either a radio equipment can perform the communication by aggregating the bandwidth allocated to each RAT or the network can determine the combination of RAT and available spectrum that provides the best connectivity and adapt the radio accordingly;

- **Scenario 3: In-band coverage or capacity improvement by relays** The deployment of relays is one IMT-Advanced technology feature to alleviate problems such as high channel impairments (e.g. high shadowing) and high traffic demand. The CRS may detect and locate the need for coverage and capacity improvement and identify the available resources. Relay parameters could be optimized using radio environment map (REM) to supply geo-location information on the coverage or capacity indicators;
- **Scenario 4: Self-configuration and self-optimization of femtocells** Initial dimensioning and planning of a femtocell network is challenging since it is difficult to evaluate how many femtocells will be deployed and where back-hauling is provided. Radio access is achieved by the RAT that defines the femtocell (IMT or IMT Advanced). Femtocells, being plug-and-play type devices, are assumed to be autonomous in specific operations as long as they are used in the operators licensed frequency bands. Furthermore, interference mitigation with neighbouring femtocells and the macro cells of the same RAT is needed to prevent QoS degradation. Systems involving femtocells are expected to be highly dynamic, therefore issues like self-configuration, self-optimization are of primary importance;
- **Scenario 5: Multi-modes coexistence and simultaneous transmission** In order to achieve multi-modes coexistence and avoid harmful interference among different RATs, it could be possible to use different frequency bands or reuse the

same frequency band with an optimum transmission power and acceptable separation distance decided by the CRS. In multi-modes simultaneous transmission, both base stations and terminals should be reconfigurable, supporting operation in different modes among multiple radio interfaces and transmitting data by using multiple radio interfaces.

### 2.1.3  Discussion

The CRS scenarios identified by the ITU-R are valuable input to the research community in the development of the CRS technology. The CRS technology is a toolbox of techniques that could be applied to different scenarios to target different goals. The scenarios identified by the ITU-R indicate that the CRS technology could be applied in both intra-system scenarios as well as between mobile communication system and other radio systems.

## 2.2  ETSI Use Cases for CR Deployment

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The ETSI Reconfigurable Radio Systems (RRS) Technical Committee (TC) is the centre of competence for CR technologies in the European Telecommunications Standards Institute (ETSI). This section describes key scenarios for CR deployment as being developed by ETSI RRS.

### 2.2.1  (TV) White Space Communication

A CR vision has been published in [4] and a number of active Working Items are currently dealing with TVWS related standardization. In the sequel, key Use Cases and Scenarios are presented as they have been derived by ETSI RRS [5].

#### 2.2.1.1  Use Case: Mid-/Long Range Wireless Access Over White Space Frequency Bands

Internet access is provided from a base station to the end users by utilizing White Space frequency bands over ranges similar to today's cellular systems, e.g. in the range of 0–10 km.

**Fig. 2.2** Mid-/long range
wireless access, no mobility
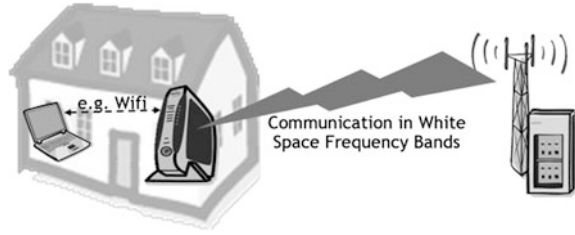


This Use Case is considered in further detail in the following Scenarios:

- **Mid-/long range, no mobility**
  In this scenario, wireless access is provided from a base station towards fixed
  devices, e.g. a fixed mounted home base station/access point. The geo-location
  from both the base station as well as from the fixed device is well-known
  (Fig. 2.2).
- **Mid-/long range, low mobility**
  In this scenario, wireless access is provided from a base station towards mobile
  devices where the users have low mobility, e.g. they are staying at their location
  or walking. In that respect, sensing results for primary users retrieved for the
  current location are not getting invalid due to the mobility of the user. The geo-
  location from the base station is well-known. The geo-location from the mobile
  device must be determined during operation, e.g. via GPS or cellular positioning
  systems.
- **Mid-/long range, high mobility**
  In this scenario, wireless access is provided from a base station towards mobile
  devices and the mobile devices may move fast, e.g. because a user is in a car or a
  train. In that respect, sensing results for primary users retrieved for the current
  location may get invalid quickly due to the mobility of the user. Thus, this use
  case sets high constraints for the detection of primary users and it can be
  questioned if high mobility will be supported in TV White Spaces at all.

### 2.2.1.2 Use Case: Short Range Wireless Access Over White Space Frequency Bands

Internet access is provided via short range wireless communication (e.g. in the
range of 0–50 m) from an access point or base station to the end users by utilizing
White Space frequency bands.

This Use Case is considered in further detail in the following Scenarios:

- **Networks without coexistence management**
  In this scenario one or more independent networks access white space frequency
  bands. The access points has to have knowledge on the incumbent users of the
  spectrum (e.g. via white space incumbent geo-location database). However, in
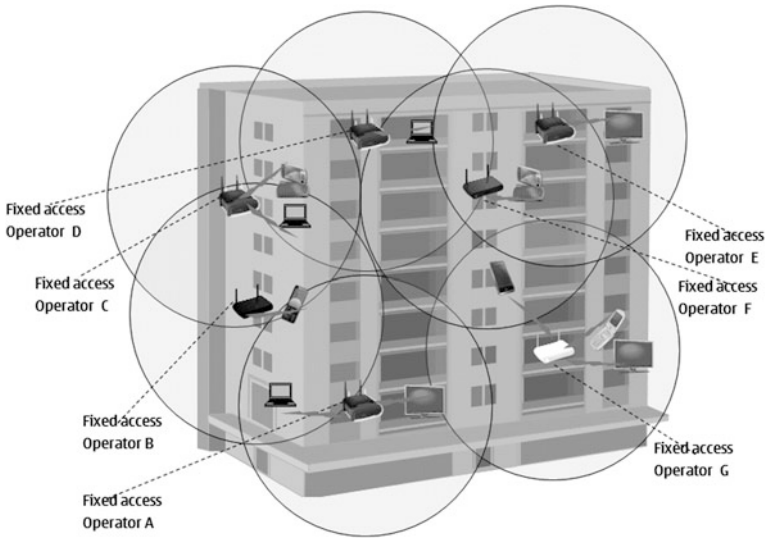
**Fig. 2.3** Use case scenario of Internet access by networks with distributed coexistence management in white spaces frequency bands

this first scenario, the different networks are uncoordinated and thus they have no knowledge on other secondary networks and users operating in the white space bands.

- **Networks with distributed coexistence management**
  In this scenario multiple networks access white space frequency bands. The different networks are independent and the backbone connectivity is provided by different network operators. This kind of scenario can happen e.g. in an apartment house, where residents independently acquire their own local area access points operating in white space frequency band. These access points can be operated and maintained e.g. by the residents themselves or the Internet Service Providers (Fig. 2.3).
  In order to work properly, this scenario requires effective coexistence mechanisms for white space frequency access.
- **Networks with centralized coexistence management**
  In this case the White Space networks in the proximity are operated in coordinated manner by a White Space operator. Examples of this kind of usage can be small scale corporate networks, networks for academic institutions etc (Fig. 2.4).
- **Hybrid of networks with distributed and centralized coexistence management**
  This scenario combines the above two scenarios, i.e. in the same neighbourhood there are both networks leveraging centralized coexistence management and networks leveraging distributed coexistence management. Examples of where this kind of scenario can happen are combinations of public and private places,
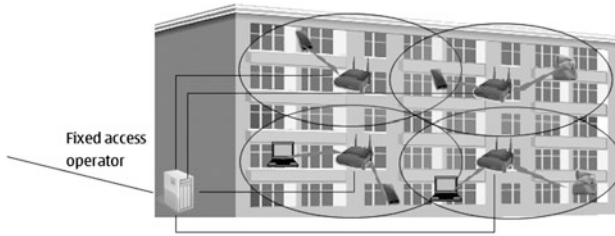
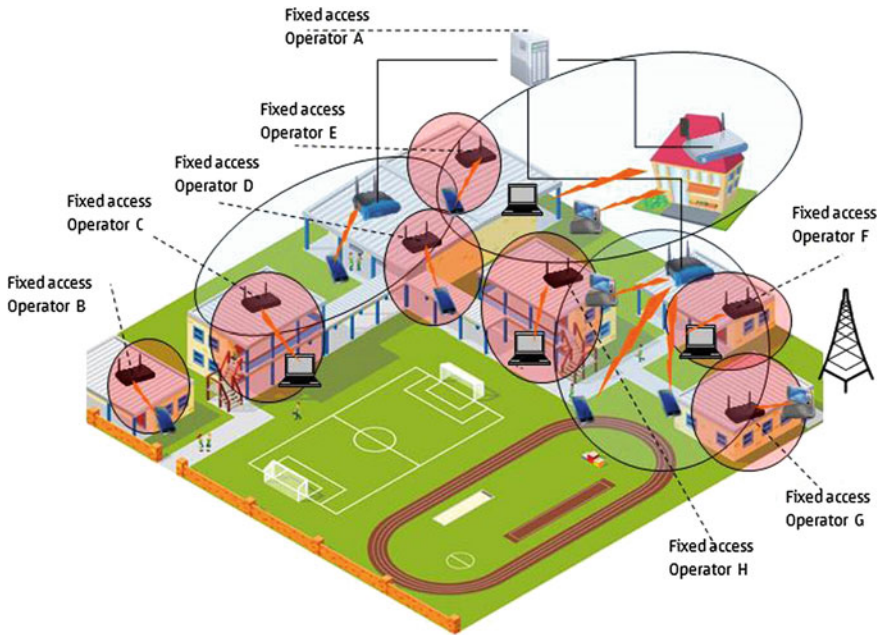**Fig. 2.4** Short range wireless access, coordinated networks



**Fig. 2.5** Use case scenario of internet access by hybrid of networks with distributed and centralized coexistence managements on white space frequency bands (*NOTE*: The coverage area of networks with centralized coexistence management is shown in blue, the coverage area of networks with distributed coexistence management is shown in red.)

like campus areas and shopping malls, where e.g. the "official" local area networks, operating under centralized coexistence management, are complemented by independent access points set up independently by some individuals (Fig. 2.5).

The overall coexistence management in this scenario is distributed, due to the existence of the independent networks.

### 2.2.1.3 Use Case: Ad-hoc Networking Over White Space Frequency Bands

In this use case the devices (user devices and other devices like access points) communicate with each other to share information, to run joint applications or services, or to execute other similar tasks. The communication happens by forming an ad hoc network operating on White Space frequency band. There can be two or more devices in the ad hoc network formed.

- **Device-to-device connectivity**
  In this case two devices (which can be similar or different) connect in peer-to-peer manner to exchange information between each other. The information can be e.g. multimedia content, or control information like measurement results shared between the devices. The devices can be similar from their capabilities (like two mobile devices), or then completely different (like a mobile device and external printer or display).
- **Ad-hoc networking**
  In this case the devices form an ad hoc network to communicate and collaborate with devices in the neighborhood. As an example the devices can be operating a localized social networking service (possibly maintained by a service provider).
- **Infrastructure supported ad-hoc networking**
  In this scenario, the infrastructure supports the creation of ad-hoc networks by providing information and knowledge about policies, available resources, context and profiles. The users receive information about e.g. the proximity of other users and the available resources (including available white space frequencies) in the neighborhood from the infrastructure via the base station and thus an ad-hoc network can be created using white space frequency bands. The link between the base station and the terminals can be realized over licensed, unlicensed or white space frequency bands.

### 2.2.1.4 Use Case: Combined Ad-hoc Networking and Wireless Access Over White Space Frequency Bands

This use case presents a combination of the ad-hoc networking use case with the short range and/or mid-long range wireless access use cases as described above.

- **Expanding the coverage of the infrastructure**
  In this scenario, a device is out of coverage of the infrastructure. An ad-hoc network is created with other devices where at least one of the other devices has access to the infrastructure. The other devices have relaying/forwarding functions in order to route the traffic from the first device towards the internet and vice versa. In such a scenario, for example, a first user is out of coverage of the infrastructure. However, this user can create an opportunistic ad-hoc network with a second user where the second user relays the traffic from the first user to the network.

- **Resolving cases of congested access to the infrastructure**
  In this scenario, one part of the network is congested. As an example, a first
  access point is congested and thus a user will have a very bad QoS when being
  connected with the first access point. While this user is not able to connect
  directly to another access point, the situation can however be improved when an
  opportunistic ad-hoc network is created with a second user where the second
  user relays the traffic to the network.
- **Direct device-to-device links in TVWS managed by access points or femto
  cells**
  In this scenario, several wireless devices are connected to the internet through an
  infrastructure device such as an access point or a femtocell. The infrastructure
  device may have wireless or fixed access to the internet. The wireless devices
  can, for example, be communicating to an access point over the unlicensed ISM
  bands, thus representing a standard home or office network setup. They could
  also be operating in the TVWS bands. Under the management of the access
  point or femtocell, certain devices may start a direct device-to-device link or
  point-to-point communication over TVWS frequencies.

### 2.2.1.5 Use Case: Sporadic Use of TV White Space Frequency Bands

In this use case, TVWS slots are only available sporadically for secondary users,
such as for example multi-mode user terminals being able to operate, among other
systems, cellular systems in licensed and unlicensed spectrum. The supported
unlicensed spectrum is assumed to include TVWS, i.e. the 470–790 MHz range in
Europe/Region 1 (Fig. 2.6).

The time-limited switch of a Base Station to operate in unlicensed spectrum (in
particular TVWS) is leading to a number of advantages which are further detailed
in the following Scenario descriptions:

- **Lighter infrastructure deployment through larger cell sizes**
  Due to the improved propagation characteristics in the TVWS bands compared
  to typical licensed bands, a large cell size is chosen which will lead to a lighter
  infrastructure deployment and thus to an overall reduced CAPEX/OPEX.
- **Increased spectral efficiency through reduced propagation loss**
  Due to the improved propagation characteristics in the TVWS bands compared
  to typical other licensed bands, a possible deployment choice is to keep a cell
  size as it is the case for the licensed band deployment. The following advantages
  are observed:

(i) Due to the improved propagation characteristics in the TVWS bands, a higher
    QoS is achieved within the given cell. However, those propagation charac-
    teristics may also increase interference issues which require an adequate
    handling (e.g. suitable frequency reuse-factor for TVWS, power management,
    etc.);
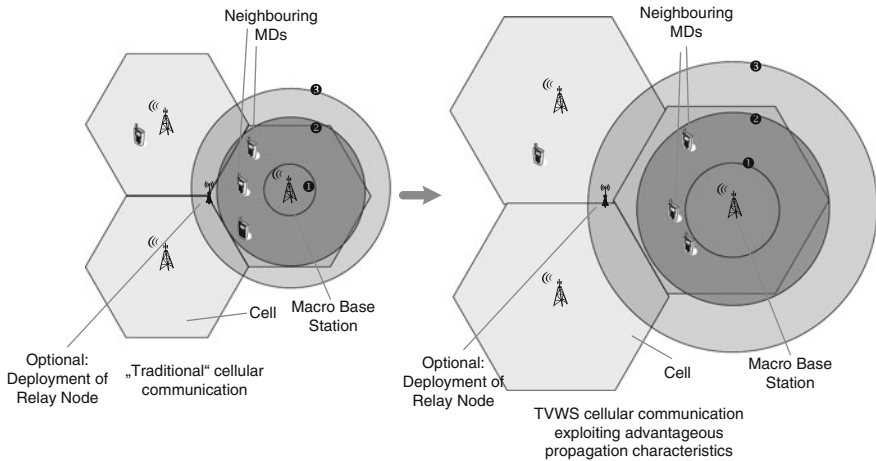
**Fig. 2.6** Reduced propagation loss in TVWS and thus improved coverage (the symbols ❶, ❷, ❸ indicate decreasing throughput levels, QoS, etc.)

(ii) Due to the improved propagation characteristics in the TVWS bands, an identical QoS is achieved within the given cell at a lower RBS/MD output power level. The inherent power consumption can be reduced;

(iii) A hybrid solution of item (i) and (ii) is possible, i.e. a moderate reduction of the RBS output power levels combined with a moderate improvement of the QoS.

- **Increased spectral efficiency through extended macro diversity**
  Due to the improved propagation characteristics in the TVWS bands compared to typical other licensed bands, a possible deployment choice is to keep a cell size (or to increase it only slightly) as it is the case for the licensed band deployment. Then, joint operation of neighboring RBS can be exploited in order to achieve a higher Macro-Diversity gain in the UL (multiple RBS are decoding jointly the received signals) or in the DL (multiple RBS are contributing to jointly optimized transmission).

- **TVWS Band-Switch in case that incumbent user re-enters**
  The TVWS usage rules vary over the geographical regions. Typically, when an incumbent system arrives, the corresponding band is no longer available for opportunistic spectrum access by secondary systems. In this scenario, it is suggested that the secondary user switches to another TVWS channel that is still available for opportunistic access—if such a channel is available. Otherwise, the secondary user is assumed to switch to operate in a suitable licensed band.

- **Carrier Aggregation between IMT bands and TV WS band**
  When performing carrier aggregation of TVWS bands with IMT bands, the system may potentially employ either TDD or FDD on TVWS bands. Since operators are adopting either TDD or FDD (depending on their licensed

spectrum) and chip vendors are supporting both TDD and FDD versions of LTE, both techniques are important to consider. The TVWS bands can be used for downlink only, uplink only, or both uplink and downlink transmission. In downlink only or uplink only, the TVWS bands will inherently use FDD. If the carrier(s) in TVWS are used for both uplink and downlink, then FDD and TDD modes are both possible for TVWS.

### 2.2.1.6 Use Case: Backhaul Link Using TV White Space Frequency Bands

In current mobile networks, there are many access points which have different capabilities, e.g. they can support different coverage. These access points can be connected with wireless backhaul link. In 3GPP LTE for example, the backhaul link between the base station and relay is wireless. The wireless backhaul link operated on the TVWS can obtain the following advantages: improve the access link capacity; supporting the existing commercial terminals; providing a simple wireless environment; providing a better channel quality because of the good propagation performance of the TVWS bands; improve the capacity of the backhaul link; supporting the sensing capability and scalable spectrum bands with lower cost.

- **Relay node backhaul link**
  In this scenario, a city or a rural area is composed by many macro cells. In a macro cell there are some hotspots or blind areas in which relays can provide the coverage. The relay which has a fixed location e.g. on the roof, could be connected to the macro cell BS with wireless backhaul link. According to the time and area in which wireless backhaul link is operated, central control point can select a TVWS spectrum for this backhaul link so that the TV service and other macro cells do not suffer harmful interference (Fig. 2.7).

### 2.2.1.7 Use Case: MBMS Operating in TV White Space Frequency Bands

Broadcasting services are widely used when transmitting the same content to a group of users at the same time in many telecommunication systems (e.g. UMTS/LTE). When performing broadcasting services, specific radio resources need to be reserved. Moreover, with the increased categories of the applications, especially some broadband applications, e.g. live TV program broadcasting, the radio resources will become quite insufficient. Therefore, the utilization of TVWS to transmit broadcasting services could meet the requirements for more radio resources. To be simplified, this use case takes the 3GPP LTE Multimedia Broadcast Multicast Service (MBMS) for example. However, other broadcasting services (e.g. UMTS) are not excluded.
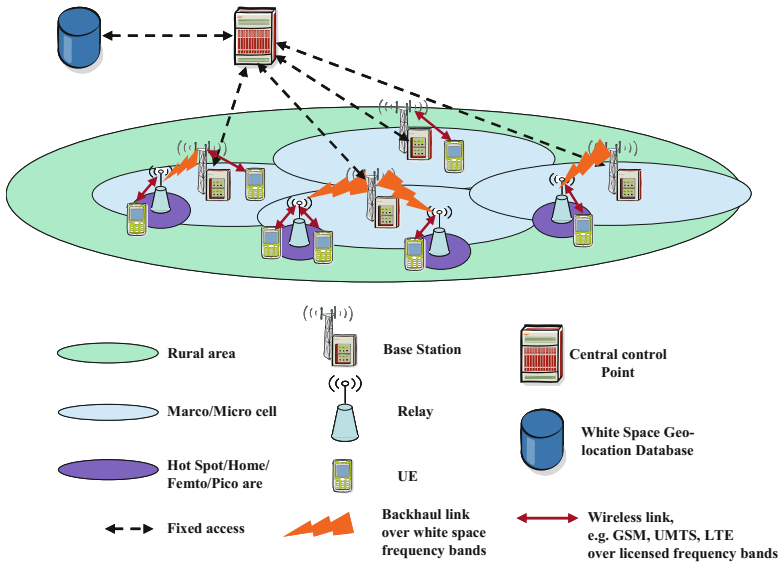
**Fig. 2.7** Wireless backhaul link operated in TVWS

- **LTE MBMS in TV white space frequency bands**
  In LTE, the MBSFN (Multimedia Broadcast multicast service Single Frequency Network) mode is realised in the manner that a group cells transmit identical waveforms with the same frequency at the same time in order to promote the frequency efficiency. Those group cells constitute an MBSFN area. A central control entity called MCE (Multi-cell/multicast Coordination Entity) is used for admission control and allocation of the radio resource used by all the eNBs in the same MBSFN area to ensure the MBSFN transmission.

### 2.2.1.8  Use Case: Machine to Machine Communications Systems Operating in White Space TV Bands

There is a strong need for communication from a wide range of machines including smart meters, smart city infrastructure (traffic lights, temperature sensors, etc.), healthcare monitoring, asset tracking and much more. These typically require long battery life (more than 5 years) and facilities such as broadcast and emergency alert. Machine communications or M2M within white space is perceived as an application of high value with a high probability of emerging.

- **Scenario for M2M systems operating in white space TV bands**
  A network of base stations is deployed, typically providing contiguous coverage across a wide area which may be much greater than the area covered by a single TV transmitter (and so white space availability is likely to vary throughout the
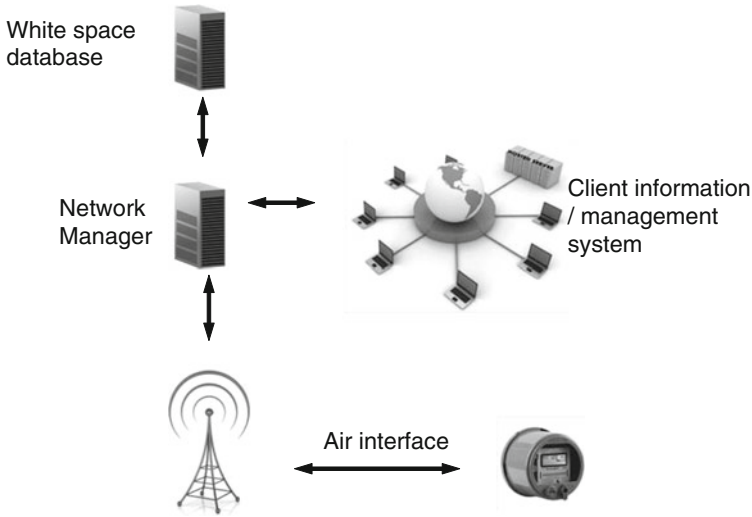
**Fig. 2.8** Example schematic of an M2M communications network

coverage area). The base stations link to a network manager which provides a
range of functions. One of these is the frequency assignment to the base stations.
To do this, the network manager consults a white space database for each of the
base stations and receives information on available frequencies which may differ
from base station to base station. The network manager uses such information to
optimally assign the frequencies to the base stations, for example, minimising
the number of adjacent cells that use the same frequency (Fig. 2.8).

## 2.2.2 Reconfigurable Radio Platforms as Enabler for CR

In order to enable the market introduction of reconfigurable radio platforms as
enabler for advanced Cognitive Radio technology, a revision of the basic regu-
lation framework for wireless communication (the R&TTE Directive) is currently
in preparation in Europe [6]. In particular, this future regulation framework will
allow for 3rd party Software Components being acquired on a per-device, per-user
basis—so called *RasioApps* [7, 8]. Each Mobile Device (MD) may thus have a
unique (radio or other) configuration which is specifically tailored to its owner(s)
and user(s). Under the current regulatory procedures, the type approval or self-
declaration based approach that is valid for a multitude of MDs (up a millions of
devices of a given type) is designed to be applied for the initial version of MD
delivered by the Original Equipment Manufacturer (OEM). Extended procedures
are required to support subsequent reconfiguration by third parties and ensure
continuing compliance of the MD.
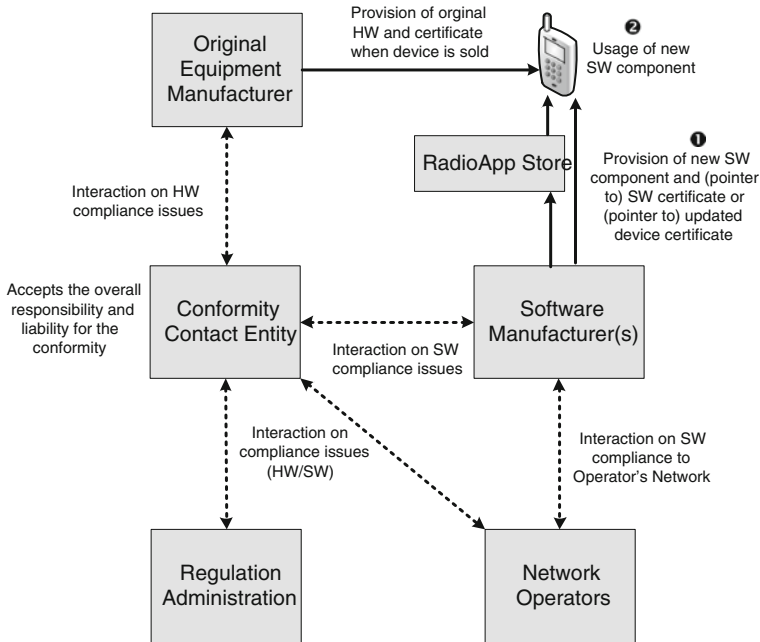
**Fig. 2.9** Responsibility for conformity of the MD is transferred to the Conformity Contact Entity after reconfiguration although the Original Equipment Manufacturer may be involved in the overall reconfiguration process [7]

As further detailed in [7], a combination of Horizontal and Vertical market models is expected to develop. It both cases the regulator expects that there be one single legal entity that takes responsibility for the conformity of the MD to all regulations. In one typical example of MD reconfiguration, the resulting responsibility structure is outlined in Fig. 2.9. In this case, a i *Conformity Contact Entity* is introduced that takes the overall responsibility for conformity of the device reconfiguration, for example as a consequence of the installation of *RadioApps*.

In this context, ETSI standard [7] details seven key use cases which illustrate the functioning of the reconfiguration ecosystem. These are summarized in the sequel.

### 2.2.2.1  OEM Establishing Initial Conformity of MD Platform

The establishment of the initial conformity and certification of the reconfigurable equipment platform by the OEM is illustrated in Fig. 2.10. This use case is very similar to the conformity testing and declaration of conformity certification that is currently used by manufacturers (OEMs) for non-reconfigurable equipment. As shown in Fig. 2.10, the following basic steps can be identified:
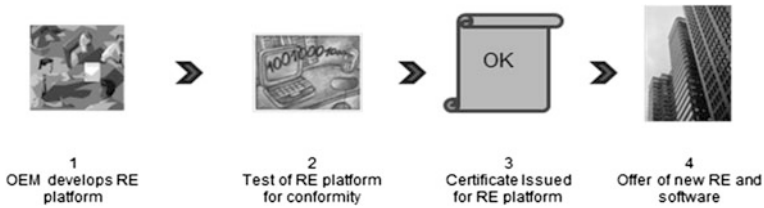
**Fig. 2.10** Use case in which OEM develops, certifies conformity and deploys an MD
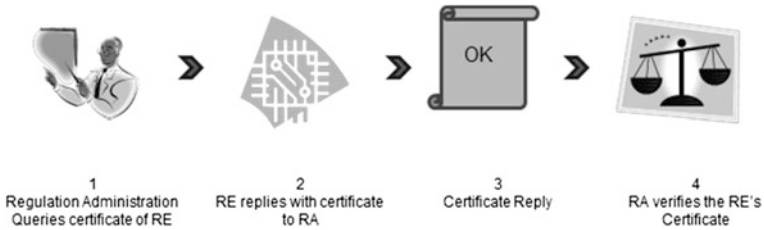


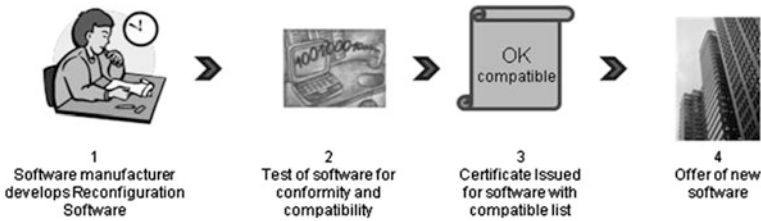**Fig. 2.11** Use case of verification of the MD's certificate of conformity

(1) The OEM designs and develops the MD.
(2) The MD is then tested, for example, by the Notified Body and the Service provider for conformity to applicable legislation and standards and a declaration of conformity is made.
(3) From the Declaration of Conformity (DoC), the OEM creates a Certificate of Conformity (CoC) for its conforming MD.
(4) The certificated MD may then be placed on the market.

#### 2.2.2.2 Certificate Verification of Reconfigurable MD

The Use Case for the verification of a Certificate of Conformity for equipment MD is illustrated in Fig. 2.11. The case may be used, for example, by a national regulator to obtain the identity of the OEM or the conformity contact entity or by a reconfigurable software vendor to determine the current configuration of the MD. The following basic steps can be identified:

(1) To verify the conformity of the equipment the inquiring party, in this illustration shown as the Regulation Administration (RA) (but it may be any other party), queries the MD to request its certificate of conformity.
(2) The MD replies to the RA (or other inquiring party) with its current certificate (or certificates).
(3) The RA (or other inquiring party) receives the certificate (or certificates).

**Fig. 2.12** Use case in which software manufacturer develops and certifies reconfiguration software

(4) The RA (or other inquiring party) verifies the authenticity of the MD's certificate to assure the conformity of the MD (including its conformity for operation in the current Member State or current service provider's network).

### 2.2.2.3 Establishing Conformity of  Reconfiguration Software

The Use Case for establishing the conformity of newly developed reconfiguration software or software components for MD is illustrated in Fig. 2.12. The following steps can be identified:

(1) The  Software Manufacturer develops reconfiguration software for applicable reconfigurable equipment together with a list of compatible MD.
(2) The reconfiguration software is tested by, for example, the Notified Body and the Service Provider for compatibility and conformity/compliance to regulations and standards for operation on the stated reconfigurable equipment and networks. With successful testing, a declaration of conformity is made.
(3) From the DoC, the software manufacturer creates a  Certificate of Conformity and a compatibility list for the conforming software product.
(4) The certificated reconfiguration software may then be placed on the market (putting into service in a Member State is subject to the verification procedure described in use case 2)

This Use Case is very similar to that of the initial OEM conformity (first use case described in 2.2.2.1) with the addition of the compatibility information list associated with the certificate.

### 2.2.2.4 OEM Upgrade (Individual or en-masse)

In some Use Cases, the reconfiguration software components may be developed by a team that includes the original equipment manufacturer and the holder of the initial certificate of conformity under which the equipment was initially marketed. This Use Case may include, for example "bug fixing", SW Upgrades, new features
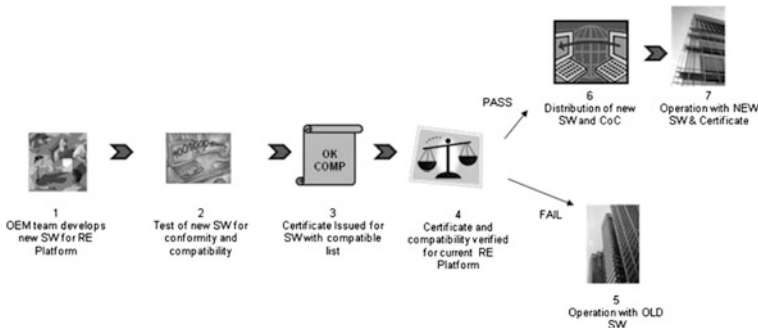
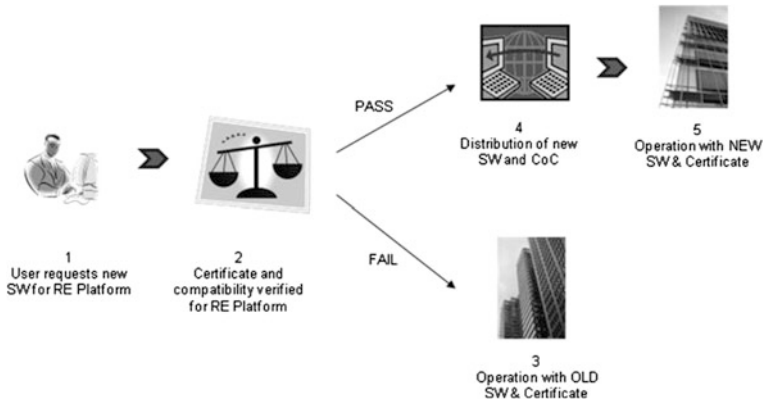**Fig. 2.13** Use case in which OEM team upgrades applicable MD en masse

and enablement of new technology such as new radio access technologies or new bands of operation.

This use case is illustrated in Fig. 2.13. This illustration considers a case where multiple MD are to be reloaded with new software by the OEM. The following steps can be identified:

(1) The OEM team develops new SW for the MD.
(2) The new SW is tested for conformity and for compatibility with the intended MD and software configuration and a declaration of conformity is made.
(3) From the DoC, the OEM team creates a Certificate of Conformity together with the compatibility list.
(4) As part of the distribution of the new configuration to the individual MD, the new components are verified for compatibility with the individual MD's current configuration.
(5) If the new reconfiguration is not compatible with the MD's current configuration, the new configuration is not loaded by the MD and the MD may continue using its previous SW and certificate of conformity.
(6) If the new reconfiguration is compatible with the MD's current configuration, the software components and associated certificate of conformity may be loaded by the MD for its use and the MD operates with the new SW and certificate of conformity (putting into service in a Member State is subject to the verification procedure described in use case (2).

### 2.2.2.5 Third Party Reconfiguration (Individual or en-masse)

In some Use Cases the reconfiguration components (e.g. software or database updates) may be provided by a team that is not associated with the original equipment manufacturing team that was responsible for the original declaration of conformity. In these Use Cases it is necessary to establish and verify the compatibility of the new configuration with the MD's current configuration.

**Fig. 2.14** Use case in which user upgrades SW MD platform

This use case may include, for example, new features, SW upgrades and enablement of new technology such as new radio access techniques or new bands of operation. In this case, the reconfiguration components may be directed to all the Reconfigurable Equipment, or to individual MD, but come from a source or sources outside the teams responsible for the MD's previous configuration.

This use case is also applicable when operational/reconfiguration database(s) that may be used by MD are updated. If the database information or protocols that affect the reconfigurable radios are updated, then a new certificate indicating transfer of responsibility to the new team for the database information or protocol updates is obtained by the reconfigured database.

This use case is illustrated in Fig. 2.14. This figure illustrates the individual MD reconfiguration use case. The following steps can be identified:

(1) The user requests new SW for the MD.
(2) The new SW certificate is verified for compatibility with the MD's current configuration.
(3) If the new reconfiguration is not compatible with the MD's current configuration, the new configuration is not loaded by the MD and it may continue using the old SW and certificate.
(4) If the new reconfiguration is compatible with the MD's current configuration, the software components and associated certificate of conformity may be loaded by the MD for its use and the MD operates with the new SW and certificate.

### 2.2.2.6 Conformity Enforcement of Reconfigurable Equipment

The Use Case for conformity enforcement of reconfigurable equipment, for example to halt improper operations, is illustrated in Fig. 2.15. The following steps can be identified:
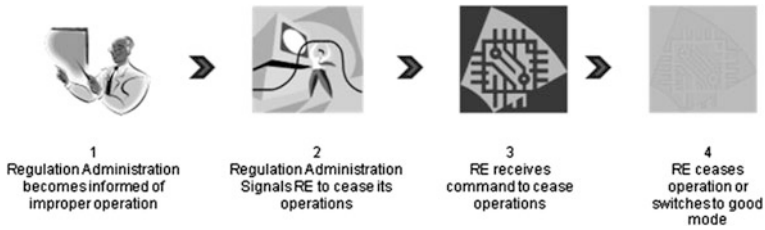
**Fig. 2.15** Use Case for enforcement in the event of improper operation of reconfigurable equipment

(1) The Regulation Administration or another appropriate body becomes aware of improper operation of reconfigurable equipment. The RA may be informed of improper operation by, for example, the SP, the OEM, other MD users or other system users.
(2) The RA signals the MD to cease its operations.
(3) The MD receives the instructions to cease the current operating mode.
(4) The MD ceases its improper functions. This may be, for example, through complete switch-off of the MD or by the MD's reversion to a known good operating mode such as a previous software version.

### 2.2.2.7 MD Discovery of Operational Database for Supporting Dynamic Reconfiguration of Equipment

In some cases the operation of the MD may be dependent on operational information obtained from an operational database (OD).

There are many methods by which the initial database discovery and contact may occur. By way of example here, an initial discovery use case is illustrated in Fig. 2.16. The following steps can be identified:

(1) The OEM or SW manufacturer embeds in the MD or the reconfiguration software a first link network address.
(2) For initial discovery the MD queries the first link network address and includes its certificate in the query.
(3) The first link network address replies with the appropriate operational database network address to the MD.
(4) The MD communicates with the operational network database.

In this procedure, note that in step 2, the MD includes its certificate in the query so that the first link network address can verify the OD requirements of the MD. In step 3, the response from the first link network address typically will include a means by which the MD can verify the authenticity of the response (to prevent the MD) being directed to a "rogue" OD.
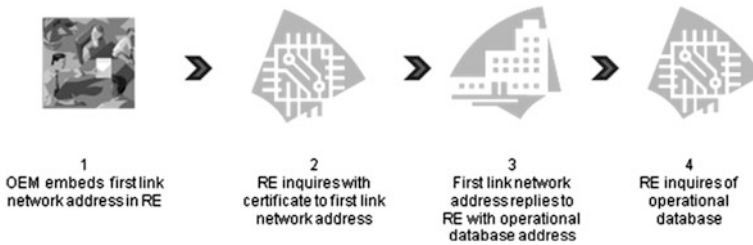
**Fig. 2.16**  Use case for discovery of operational database

## 2.3  Scenarios for CR Deployment: Visions from Research Projects

**Marja Matinmikko[1] and Jarkko Paavola[2]**

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[2]Turku University of Applied Sciences, Turku, Finland

This section presents a set of scenarios proposed within research projects that participated to COST-TERRA activities. Although the section will not aim to cover all the projects in the field of CR, it will describe a wide set of scenarios relevant to many projects, highlighting for each of them the opportunities and the corresponding research issues. Projects that are included in this review are:

- EU funded OneFIT (Opportunistic networks and cognitive management systems for efficient application provision in the Future Internet) project in 2010–2012;
- Finnish COGNAC (Cognitive and opportunistic wireless communication networks) project in 2008–2010;
- Finnish CORE and CORE+ (Cognitive radio trial environment) projects in 2011–2014;
- Finnish WISE/WISE2 (White space test environment for broadcast frequencies) projects in 2011–2014.

### 2.3.1  OneFIT Project

The main objective of the OneFIT project in 2010–2012 was to design, develop and validate the concept of applying opportunistic networks and respective cognitive management systems for efficient application/service/content provisioning in the Future Internet, see [9]. The motivation stemmed from the requirement to satisfy the increased demand for new applications and services through increased efficiency in resource provisioning and utilization. The project developed the concept of Opportunistic Networks that are operator-governed, temporary and coordinated extensions of the infrastructure. They are dynamically created—through operator spectrum, policies, and information—in places and at time instants they are needed

to deliver multimedia flows to mobile users, in the most efficient manner. They can include network elements of the infrastructure and devices potentially organized in an infrastructure-less manner.

The project addressed and developed solutions for the following five scenarios [9]:

- **Scenario 1: Expanding infrastructure coverage**
  In this scenario, a device cannot connect to infrastructure due to lack of coverage or mismatch of radio access techniques. Opportunistic network is created to serve a device that has no connection to the infrastructure.
- **Scenario 2: Resolving cases of congested access to the infrastructure**
  A device cannot connect to infrastructure due to congestion. Opportunistic network is created to route traffic to decongested area.
- **Scenario 3: Local infrastructure-less service provision**
  Opportunistic network is created among devices without infrastructure components to serve local needs reducing the traffic load that has to go through the infrastructure.
- **Scenario 4: Cost-efficient bridging to the outside world via opportunistic networks**
  Opportunistic networks are created in specific service areas to optimise the resource use by allowing traffic aggregation.
- **Scenario 5: Opportunistic network using multiple access points for increased backhaul capacity**
  Opportunistic network is created across multiple access points to resolve congestion in the backhaul.

The project developed the concept of opportunistic network to address these scenarios with focus on the CRS based solutions for the efficient management of these networks and information exchange among the elements. To accomplish this, the project developed [10]:

- *Cognitive management systems*. Two types of systems were developed, namely "*Cognitive systems for Managing the Opportunistic Network*" (CMONs) and "*Cognitive management Systems for Coordinating the Infrastructure*" (CSCIs). They provide the means for determining the suitability, creating, modifying and handling forced terminations of an opportunistic network in the five scenarios;
- *Control Channels for the Cooperation of the Cognitive Management Systems* (C4MS). Control channels were developed to enable the delivery of information from the infrastructure towards the Opportunistic Networks and provide the means for the management of Opportunistic Networks.

### 2.3.2 COGNAC Project

The Finnish COGNAC project in 2008–2010 has developed scenarios for CRS which are summarized in [11]. COGNAC project built upon its predecessor, the Finnish CHESS (Channel State Estimation and Spectrum Management for Cognitive Radios) project in 2006–2007 summarized in [12]. The CHESS project

focused on ad hoc type of operations with spectrum sensing as the key CRS technology. The COGNAC project shifted the focus towards applications of CRS technology to mobile communication systems instead of ad hoc systems and also considered other CRS technologies beyond spectrum sensing. The COGNAC project has predicted that evolution of CR systems is expected to start from optimising the use of spectrum and progressing ultimately towards sharing all mobile communication network resources in the global scale. The following four scenarios (steps) were identified in [11]:

- **Scenario 1: Optimizing the use of spectrum**
  First the focus is on optimizing spectrum use in the band including spectrum sharing between different systems in the same band or using the band more efficient by a single system exploiting CRS technology.
- **Scenario 2: Network optimization**
  Autonomous network optimization becomes more and more important as the number of base stations/access points of mobile systems and overlapping networks increases. The resource usage optimization of the resulting heterogeneous networks that partly operate in same frequency bands must be performed dynamically by the systems themselves. Networks will be able to support the adaptation to different environments, using several different radio interfaces. Intelligent selection of the radio interface or other available channel is made cognitively in order to select the best method. As the experience with the operation in heterogeneous environment is gained, it will become feasible to include aspects of e.g. database based machine learning features into the systems, allowing them to make predictions and pre-adaptations their behaviour to match future conditions.
- **Scenario 3: Access to all local resources**
  Flexible access rights are introduced to all local network resources, not only spectrum. Nodes of a network, e.g. wireless devices, not necessarily wish to communicate but they also bring their resources to the network. Different types of resources include radio resources (e.g. power, frequency, time and space), built-in resources (e.g. mass storages, processing units, and batteries), user interface resources (e.g. speakers, microphones, and cameras), social resources (e.g. individuals and groups), and connectivity resources (e.g. air interfaces). Resources are shared widely.
- **Scenario 4: Access to world-wide resources**
  Concepts of cloud computing become relevant for wireless subscribers with needs for computing and other services. Gradually all networks resources can be managed and shared in cognitive network. Evolution of CR systems and cloud computing leads to mobile clouds.

The investigations in the COGNAC project indicated that the CRS technology was applicable to several areas in mobile communication systems to improve the resource usage ranging from optimising the spectrum use to other resources as well.

### 2.3.3  CORE Project

The Finnish CORE project (2011–2012) in the Tekes Trial program continued the work of the COGNAC project and expanded the approach to cover also business aspects. The focus was returned back to spectrum, it being the key resource to be studied in the context of mobile communication networks. The CORE project developed four scenarios for future cognitive spectrum sharing networks by using value creation and capture as two defining axes. Six key ecosystem players were identified including spectrum regulator, dominating  mobile network operator (MNO), challenger MNO, infrastructure vendor, equipment vendor, and content provider. The following scenarios were developed by taking into account the dimensions of the degree of licensing and source of customer attraction and lock-in (services versus devices) [13, 14]:

- **Scenario 1: Cruella de Vil**
  The regulator plays the key role and allocates available spectrum mostly to dominating MNOs, and thus does not enforce spectrum sharing. MNOs can act as a smart bitpipe that exploits its vast spectrum resources to offer mobile services and connectivity to its wide customer base.
- **Scenario 2: Snow White**
  The regulator allocates spectrum to both challenger and dominating MNOs and enforces sharing indirectly. This leaves the operators to compete with more diverse strategies as they have to become an efficient bit-pipe in order to exploit their limited spectrum resources more efficiently in the growing competition.
- **Scenario 3: Cheshire Cat**
  The regulator promotes sharing and opens up more unlicensed spectrum opportunities. Non-MNO service providers exploit these newly opened unlicensed spectrum opportunities entering the field currently dominated by MNOs, which reshapes the market dynamics, especially of dominating MNOs' business.
- **Scenario 4: Gyro Gearloose**
  The regulator promotes sharing. The MNOs' business is affected by new innovative and focused devices that directly connect to specified services. Also, there are cases where device vendors and platform providers are merging to create "Gyro Cats," such as Nokia-Microsoft or Google-Motorola.

The CORE project focused specifically on how mobile communication networks could gain access to new spectrum resources via spectrum sharing using the CRS technology. The studies concluded that a promising way for MNOs was to share spectrum from other type of  incumbent spectrum users with rules and conditions that resemble current exclusive licensing to guarantee predictable quality of service (QoS) in the shared bands.

### 2.3.4  CORE+ Project

CORE+ project (2013–2014) [15] in the Finnish Trial program continued the work of the CORE project with a focus on a special scenario for mobile communication systems with spectrum sharing using the new Licensed Shared Access (LSA) concept that will be introduced in more detail in Sect. 2.6. The LSA concept allows a limited number of authorised users to operate in the same frequency band with sharing rules that provide certain QoS for all users. The LSA approach when applied to mobile communication systems sharing spectrum from other type of incumbent spectrum users refers to the Authorised Shared Access (ASA) concept [16]. ASA allows the MNO to obtain a license from the regulator to operate in the band with pre-determined rules and conditions agreed with the regulator and incumbent spectrum that resembles exclusive licensing and offer guaranteed QoS. To become successful, the ASA concept has to benefit all involved stakeholders, namely spectrum regulator, incumbent spectrum user, and the ASA licensee which can be a dominating MNO or a challenger MNO. Within the ASA scenario, the following business benefits have been initially identified for the key stakeholders:

- **Spectrum regulator** is responsible for issuing ASA licences and negotiating sharing conditions/usage requirements. The ASA concept could allow the regulator to maximise the value of the spectrum assets through sharing while still retaining control over the spectrum. It allows the balancing of the spectrum demands between different wireless systems by improving the spectrum availability via sharing.
- **Incumbent spectrum user** (non-MNO) can take advantage of the ASA concept by offering parts of its unused spectrum to be shared with the MNO and possibly get compensation for it.
- **Dominant MNO** could gain access to new low cost ASA bands to satisfy the growing traffic demand without strict coverage obligations. It could obtain significant savings in the network expenditure by acquiring new ASA spectrum and deploying base stations there using existing sites maintaining the dominant position.
- **Challenger MNO** could gain access to new low cost ASA spectrum bands which should be particularly appealing to Challenger MNOs, as they often suffer from the lack of sufficient amount of spectrum. They could gain access to new localised business opportunities challenging the dominating MNOs.

### 2.3.5  WISE and WISE2 Projects

WISE projects (2011–2014) focus on incumbent protection methods for shared spectrum. In the WISE project TV white space test (TVWS) environment was deployed in Turku, Finland. Two incumbent scenarios are considered for TVWS:

- **TV signals**: Spectrum occupancy for TV broadcasting is stable and the information on transmission sites can be obtained from the national regulator.
- **Wireless microphones**, or program making and special event (PMSE) equipment in general: this use case is hard to predict, and therefore the incumbent user is more complex to protect. For example in Finland, a radio license is required for wireless microphones. However, authorities have no possibility to guarantee that all users follow the registration process.

Detailed information can be found from the ECC Report 159 [17] with complementary studies in ECC reports 185 [18] and 186 [19].

In WISE2 project the utilization of test environment was extended for piloting following use case scenarios with TVWS technology:

- Rural broadband: TVWS can be used as a last mile connection to provide broadband access for rural areas, since TV frequencies have good propagation properties.
- Video surveillance: Wireless video surveillance systems utilize WLAN or cellular networks. These systems have issues with capacity and cost. TVWS could provide a cost efficient way for extra capacity.
- Smart grid: TVWS is tested for communication between control stations. Data rates are very low but delay requirements are strict. TVWS is considered for replacing satellite link. Typical distances considered for the transmission link are in the order of several tens of kilometres.
- ITS in public transport: Public transport has many wireless applications. For TVWS wireless ticket purchasing and connection between bus and information screen at the bus station are piloted before devices supporting mobility and handover are available.

Additionally, in WISE2 project, incumbent protection for ASA/LSA spectrum sharing model is investigated. Two incumbent scenarios are considered for ASA/LSA in 2.3–2.4 GHz frequency band [19]:

- **Wireless cameras**, or PMSE equipment in general: Several different use cases such as cordless, mobile and portable video links are included.
- **Military use**: From military side unmanned aircraft systems (UAS) use the frequency band. UAS use telecommand in the uplink and video links in the downlink direction.

It is assumed that the database approach is used to control spectrum sharing. Database must contain information on available frequencies, and the incumbent use on those frequencies. A device queries database with location and optionally operating parameters. The database sends a response containing frequency and transmission power information.

The approach in the project for the incumbent protection is two-fold. The PMSE manager has been developed to collect and control information on incumbent use. The manager communicates information to the database. A simple and easy-to-use user interface, which allows also automatic registration if

supported by devices, will make it feasible to manage incumbent devices even when their use is hard to predict spatially or temporally.

On the other hand, RF measurements are performed in the project to verify defined protection ratios between incumbent use and new devices in the frequency band. Measurements are also carried out to validate database operations.

## 2.4 DSA Application Scenarios: Cases of Finland and India

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### 2.4.1 Introduction

The paradigm of regulation has shifted from pure coordination and planning to the creation of a competitive and sustainable environment for various services, including telecommunications. Technologies have also evolved to accommodate flexibility in spectrum management. As a result countries are migrating in different degrees, and at different speeds to flexible spectrum management regimes. This is also augmented by the exponential increase in mobile data traffic that is expected to grow at a compound annual growth rate of 92 % from 2010 to 2015, reaching 6.3 Exabyte per month by 2015 [20]. In addition, this study shows that mobile internet will grow from 14 million at the end of 2010 to 788 million by the end of 2015. This phenomenon is happening in both developed countries such as Finland as well as in emerging countries such as India. For example, wireless Internet subscribers in India have reached about 143 million and continue to grow at an exponential rate [21].

This potential increase for mobile Internet services is pushing governments to better manage their spectrum resources. There is a trade-off before the policy maker, between the number of operators to be allocated spectrum and spectrum block allocated to each operator. In some emerging countries, the decision has been made in favour of competition and hence the associated maximal usage of allotted spectrum. On the other hand, in many advanced countries, such as those belonging to the European Union, the policies favour a limited number of operators with more spectrum blocks for each operator. In addition, these advanced countries had favoured technology harmonisation, while emerging countries favoured technology competition. Given this disparity in spectrum policies and market structure in different markets, it is interesting to analyse the future evolution path for spectrum management in these two extreme scenarios. Following Table 2.1 contrasts the spectrum allocation and market structure in the representative countries of Finland and India.

**Table 2.1** Comparison of policies across India and Finland (adapted from [26])

| Factor | In India | In Finland |
|---|---|---|
| Average spectrum allocation per operator per License Service Area | 2 × 6 MHz in 900; 2 × 4.5 in1800 for 2G; 2 × 3 MHz in 800 for 2G/3G; 2 × 5 MHz in 2100 for 3G; 20 MHz unpaired in 2300 MHz for BWA | 2 × 11.3 MHz in 900; 2 × 24.8 MHz in 1800; 2 × 15 MHz in 2100; 4.8 MHz unpaired in 2100; 2 × 20 MHz in 2600 MHz |
| Market Fragmentation (measured as HHI ranging from 0 to 1; 1 being monopoly) | 0.15 | 0.33 |
| Harmonization Policy of the Government | GSM in 900/1800; CDMA in 800; WCDMA in 2100; BWA in 2300 MHz; No unified view | GSM, WCDMA and LTE adopted in different spectrum blocks as per European harmonisation measures [69] |

As is clear from the above Table, while Finland has taken the route of less number of operators, less market and spectrum fragmentation, increased spectrum assignment for each operator and a globally harmonized policy on spectrum allocation, India has taken a very different route, highlighted by intense competition, heavily fragmented market and spectrum allocation and no unified long term view of spectrum allocation policy.

### 2.4.2 Policy Options for Reacting to the Exponential Increase in Demand

Even though spectrum policy may differ depending on country and local circumstances, the national regulatory authorities (NRAs) have responded in general in the following ways:

(i) Allocate additional spectrum to mobile services. For example, release of the digital dividend spectrum in the 700 MHz;
(ii) Mandate  refarming of the traditional 2G spectrum band, especially in 900 MHz and 1800 MHz for a more spectrally efficient (e.g. 3G and 4G) technologies so that the given spectrum is efficiently used;
(iii) The creation of secondary market that allows  spectrum trading;
(iv) Consider allowing non-exclusive sharing of spectrum opportunistically using Dynamic Spectrum Access (DSA) technologies such as CR.

Out of these four options, the last two depend on the existing  spectrum allocation policies and the market structure that vary across countries. Trading can be defined as a process in which spectrum changes its ownership, allowing  spectrum transactions either geographically, by frequency or time. Many authors point out that such spectrum

markets are viable if sufficient numbers of market participants exist and the amount of tradable spectrum is balanced to the demand [22, 23]. Trading can be mutually agreed between parties or performed in an open spectrum market. As opposed to trading, in an opportunistic spectrum access, the secondary user does not require a formal permission from the primary spectrum holder [24], but it accesses the available spectrum opportunistically (non-coordinated), making sure that it does not interfere with the primary user, e.g. through a spectrum database or using CR sensing technologies. However, the primary spectrum holder may still be willing to get an economical compensation from allowing secondary access to its spectrum [25]. The non-exclusive spectrum sharing may be operator induced or end-user induced. We discuss in the following section these two possibilities and their possible presence in different markets.

### 2.4.3 The Causal Model of Spectrum Policy

The model in Fig. 2.17 [26] summarizes the spectrum policy differences between a country practicing spectrum harmonization such as Finland and a country practicing market driven spectrum policy such as India. It uses "shifting the burden" archetype [27] which describes how the chosen path for solving a problem makes difficult to change to another alternative path and thus creating a path dependency.

As shown in Fig. 2.17, the increased disparity in capacity and coverage can be handled by enforcing a stronger harmonization policy leading to a more equal and efficient initial allocation and assignment of spectrum. This subsequently leads to the decrease of the disparity and a balancing loop 'B-Harmonization' which on a rough level corresponds e.g. to the Finnish spectrum policy as well as many other European markets.

On the other hand efficient centralized allocation means that operators do not need to conduct much market based sharing (or trading) and that end users do not have many options in terms of the different radio access possibilities which subsequently means that secondary market sharing or trading mechanisms between operators and CR type of capabilities in devices are not required. Operators may cooperate by infrastructure sharing or even by spectrum sharing, but they do not need a market based co-operative trading or opportunistic end user access. The inability of the market to redistribute the spectrum resources in turn leads to a reinforcing loop ('R-Efficiency through Centralized Planning') that possibly locks the market on a path of enforcing a harmonization policy. In this situation, it is expected that opportunistic access is made possible through operator centric devices.

On the other hand, the Indian market has followed the opposite dynamics. Since the initial spectrum allocation is inefficient, the increasing mobile service demand has been handled by the market in the form of co-operative trading between operators (i.e. national roaming) and opportunistic end user access (i.e. many data plans per user through multi-SIM devices). This in turn has led to what can be seen as a kind of a secondary market activity and subsequently to the decrease of the
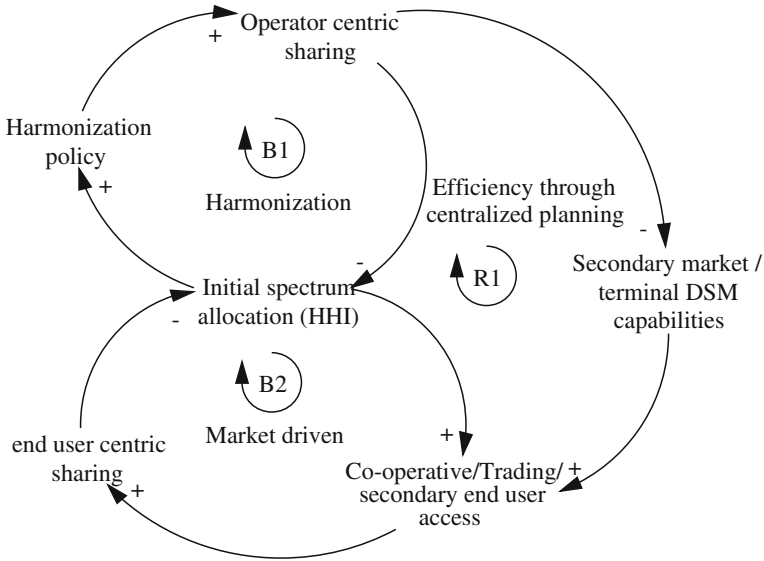
**Fig. 2.17** Feedback model indicating the differences between spectrum policies (adapted from [26])

disparity and a balancing loop 'B-Markets'. In this case, when the market solves the disparities in coverage and capacity it leaves little space for a harmonization policy which in turn leads to a larger need of secondary market sharing and trading mechanisms between operators and CR capabilities of end-user terminals in order to efficiently use and redistribute the radio resources. This in turn leads to a reinforcing loop 'R-Efficiency through Centralized Planning' that works in the opposite direction when compared to harmonized markets such as Finland. The exponential increase in multi-SIM handsets is an example of this type where the end-user devices have CR like capabilities to access networks and hence spectrum of choice.

The fact that these two markets can be seen as being locked on two opposite paths have a significant impact on their future evolution, especially regarding the introduction of DSA technologies. While harmonized markets may favour mobile operator centric spectrum sharing, highly competitive markets may fit better with end-user centric spectrum sharing.

### 2.4.4 Conclusions and Future Evolution Scenarios

Based on the previous model, it appears that the Finnish market is set on a path of pursuing a harmonization policy where demand for wireless broadband in the future will be met by a centrally planned efficient initial allocation, the increasing adoption of spectrally efficient technologies and by releasing exclusive digital dividend

spectrum. India on the other hand seems to be on a path of pursuing a more market based policy that could lead to higher activity in the secondary markets (as is already the case with national roaming and multi-SIM phones). The Indian market structure thus can be seen as having a better fit with the CR technologies which could lead to a more rapid diffusion of CR systems in  India (and in other developing markets following the same market structure). Therefore when it comes to the diffusion of CR technologies, the  emerging markets are in a good position to do technology leap-frogging much similar to the way they did in skipping analogue wireless technologies and adopting the second generation digital cellular systems.

## 2.5  Mobile Communications and Need for CR

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This section focuses on the spectrum matters of  cellular mobile communication systems and the emerging role of CR in that regard. Starting from the mobile traffic growth predictions, the current status of mobile spectrum is presented. Future directions are depicted including the potential for new spectrum bands for the mobile service and the introduction of CR technology to facilitate  spectrum sharing between a mobile communication system and  incumbent spectrum users.

### 2.5.1  Mobile Traffic Growth

Back in 2006, the International Telecommunication Union Radiocommunication (ITU-R) sector published a comprehensive forecast of the global mobile tele-communication market in Report ITU-R M.2072 [28]. The report identified a number of new wireless applications and services and predicted a strong growth in the mobile traffic in the time span 2010–2020.

In preparation for the World Radiocommunication Conference in 2007 (WRC-07), the ITU-R developed a methodology [29] to estimate the spectrum requirements of IMT systems based on the global traffic forecast in 0 and technology developments summarized in [30], see also [31]. The results of the spectrum requirement calculation studies for IMT systems in the years 2010, 2015 and 2020 are presented in Report ITU-R M.2078 [32] including the spectrum requirements for two distinct radio access technology groups (RATGs):

(1)  pre-IMT, IMT-2000 and its enhancements (RATG 1) and
(2)  IMT-Advanced (RATG 2).

**Table 2.2** IMT spectrum demand in MHz prior to WRC-07 from ITU-R M.2078 [31]

| Market setting | RATG 1 | | | RATG 2 | | | Total | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2010 | 2015 | 2020 | 2010 | 2015 | 2020 | 2010 | 2015 | 2020 |
| Lower | 760 | 800 | 800 | 0 | 500 | 480 | 760 | 1300 | 1280 |
| Higher | 840 | 880 | 880 | 0 | 420 | 840 | 840 | 1300 | 1720 |
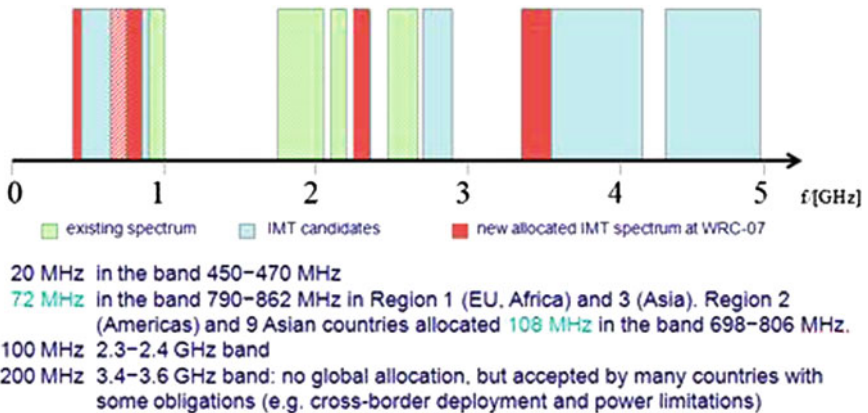


**Fig. 2.18** Spectrum allocations at WRC-07

These two RATGs collectively cover the family of IMT systems. The study concluded that between 760–1720 MHz of spectrum needed for IMT systems depending on market setting and year as presented in Table 2.2. The study took into account the total mobile telecommunication traffic from [28] and considered the relevant radio systems that are capable of carrying this traffic.

The total mobile traffic was divided among four different RATGs where the first two covered IMT systems, while RATG 3 was defined as "existing radio LANs and their enhancements" and RATG 4 as "Digital mobile broadcasting systems and their enhancements". Thus, the study took into account all relevant radio systems and concluded the spectrum requirements for the IMT systems, i.e. RATGs 1 and 2.

Based on these studies, the ITU-R decided at WRC-07 to globally allocate additional spectrum between 392 MHz (EU, Africa, Asia) and 428 MHz (Americas, CHN, KOR, IND, JPN, NZL) to the mobile service with identification to IMT. The detailed allocation is shown in Fig. 2.18. It should be noted that this allocated spectrum did not become available immediately, but requires further collaborative work on international, regional and national level.

To underline the apparent fact of the increasing mobile traffic demand throughout the previous years, ITU recently published its annual MIS Report (Measuring the Information Society) 2013, showing two benchmarking tools to measure the information society: the ICT Development Index (IDI) and the ICT Price Basket (IPB). In the Top-Ten ranking of the IDI, 8 European countries

**Fig. 2.19** Comparison of traffic from Report ITU-R M.2072 [28] prior to WRC-07 and Report ITU-R M.2243 [35] prior to WRC-12. Source: [35]
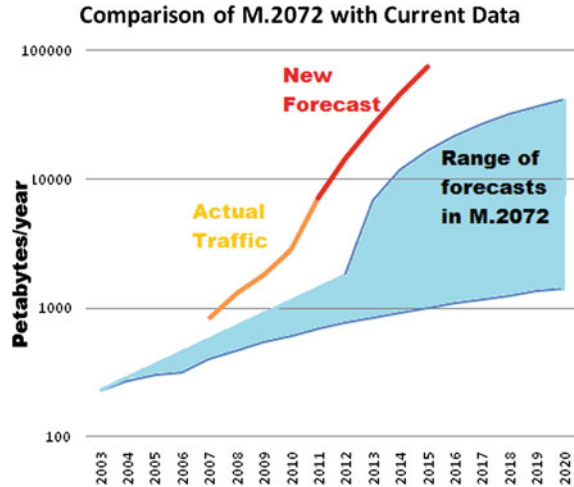


(including Sweden, Finland, United Kingdom) can be found beside Korea (#1) and Hong Kong (#10) [33].

There are several studies [32, 34] clearly showing that the trend of increasing traffic demand is also continuing in the future. In particular, the ITU-R has prepared a new report [35] on the market and traffic forecasts for IMT, collecting new traffic forecasts from a number of sources. This study calculated an increase in the mobile traffic resulting mainly from data, which exceeds the values of ITU-R M.2072 (WRC-07) by a factor of >5 already today as shown in Fig. 2.19.

To address the  traffic growth which today is foreseen to be even stronger than previously anticipated, the ITU-R prepared an input for the previous WRC-12 to include a new agenda item for the next WRC-15 to review the spectrum availability for IMT, based on new studies presented in Report ITU-R M.2243 [35] on the spectrum requirements and additional allocations to the mobile service for broadband systems including IMT.

With the new traffic forecast summarized in Fig. 2.19 for the years 2015–2020 and further forecasts for the year 2025 from Report ITU-R M.2243 [35], it is obvious that the increasing traffic has to be accommodated somehow within the next decade. This can be done in different ways:

1. by allocating additional spectrum for the mobile service;
2. by re-using existing spectrum allocations more efficiently (e.g. refarming, carrier aggregation and other new technologies);
3. by using new methodologies to access spectrum (e.g. shared spectrum access).

To address the *first item*, the ITU-R will consider the allocation of additional spectrum for the mobile service at WRC-15. In preparation for WRC-15, the ITU-R has estimated the spectrum requirements of IMT systems as well as other mobile systems (such as RLAN).

For the *second item*, spectrum refarming is already implemented in various European countries by the majority of mobile operators (see also Table 2.4). This enables the operators to re-use existing spectrum with new, more efficient and better performing technologies. A very well suited and already widely deployed technology is LTE (Long Term Evolution) and in the future its enhancements "LTE-Advanced" (LTE-A). LTE-A—beside other new capabilities—also allows the aggregation of single carriers in different bands, called "carrier aggregation", to create one larger carrier (e.g.: 10 MHz @ 800 MHz + 10 MHz @ 900 MHz = 20 MHz carrier) and consequently enable higher data rates in given cell. LTE-Advanced can be implemented in existing LTE-networks with relatively low effort (e.g. SW-modification together with possible very small hardware extensions, but no site-reconstruction). According to GSA—The Global mobile Suppliers Association as of October 2013, 456 operators are investing in LTE and there are 213 commercially launched LTE networks deployed in 81 countries [36].

For the *third item*, new developments in the spectrum access methodology will further improve the spectrum use. There are different concepts under development such as Licensed Shared Access (LSA) and its application to mobile, i.e. Authorised Shared Access (ASA). The Radio Spectrum Policy Group (RSPG) prepared a response to the European Commission's request for an opinion on spectrum regulatory and economic aspects of LSA [37], concluding that "Licensed Shared Access (LSA) could provide new sharing opportunities on a European scale under a licensing regime, while safeguarding national current spectrum usages which cannot be refarmed. It is not intended that LSA will be an initial or temporary phase prior to the refarming of any band." More detailed information regarding ASA/LSA can be found in the following Sect. 2.6.

A mixture of all three approaches is envisaged to be required to successfully meet the growing traffic demand. Despite the above mentioned ways to accommodate the traffic, there is an increase in the needed/desired data-rates and higher data-rates need also wider carrier bandwidth. For that reason, the above mentioned methodologies have to be applied in higher frequency bands.

### 2.5.2 Current Status in Cellular Mobile Spectrum

Currently various frequency bands are allocated exclusively to mobile IMT (Table 2.3), with different detailed implementations across the three ITU-R regions.

Based on the spectrum allocations, different roll-out strategies have been implemented across Europe based on technology availability. The former existing strict separation of technologies and frequency bands has been changed and the same technology is available across different bands (mainly due to spectrum refarming), leading to the following technology usage across Europe as presented in Table 2.4.

**Table 2.3** Globally allocated frequency bands for IMT

| Band (MHz) | ITU radio regulations footnotes identifying the band for IMT |
|---|---|
| 450–470 | 5.286AA |
| 698–960 | 5.313A, 5.317A |
| 1710–2025 | 5.384A, 5.388 |
| 2110–2200 | 5.388 |
| 2300–2400 | 5.384A |
| 2500–2690 | 5.384A |
| 3400–3600 | 5.430A, 5.432A, 5.432B, 5.433A |

### 2.5.3 Future

As explained above, the currently available spectrum allocation for the mobile service is quite comprehensive and today sufficient to carry the current traffic load. However, recent ITU-R investigations summarized in this section have identified a strong increase in the mobile traffic in the future leading to increasing spectrum demand. This possible need for new spectrum for the mobile service is the topic of the next WRC-15.

In parallel to the process of possible new spectrum allocations, there is the process of actually making these bands available for mobile network operators to deploy their networks. From the IMT spectrum identifications summarised in Table 2.3, not all bands are available today in all European countries. Typically, a band allocated to the mobile service already encompasses some incumbent spectrum use prior to the allocation and clearing of the band for mobile is a time-consuming and costly process. For example, the 2.3–2.4 GHz band that was globally allocated to mobile service at WRC-07 encompasses a range of other incumbent users in Europe, such as military, programme making and special events (PMSE), etc.

To speed up the process of making these bands available while preserving the rights of the incumbents, a new sharing based approach has emerged taking advantage of the CR technology. Spectrum sharing under the recently introduced LSA framework can offer the benefits of traditional exclusive licensing while guaranteeing incumbents' rights. It facilitates spectrum sharing between an incumbent spectrum user and a new licensee with rules and conditions that can offer predictable QoS to both. This LSA approach can be more appealing for the mobile communication systems to share spectrum bands from other type of incumbent spectrum users in contrast to unlicensed sharing such as unlicensed access to the TV white spaces.

**Table 2.4** Technologies deployed across the different frequency bands

| Band (MHz) | Former technology | Current technologies | Remarks |
|---|---|---|---|
| 450 | | | Rarely used for cellular |
| 700 | – | – | Allocated in principle, but bandplan t.b.d. |
| 800 | – | LTE | |
| 900 | GSM | GSM & UMTS | |
| 1800 | GSM | GSM & LTE | |
| 2100 | UMTS | UMTS | |
| 2600 | – | LTE | |
| 3500 | WiMax | WiMax & LTE | Only partly used |

## 2.6 Licensed Shared Access as an Example of Upcoming Implementation in Europe

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### 2.6.1 Background

Wireless and mobile traffic growth is predicted to explode and grow exponentially by a paramount rate through 2025 [38]. On top of existing wireless applications, new technologies will require additional spectrum resources as they expand in new areas, in particular Machine-To-Machine communication, Wearable Devices communication, video streaming etc. will take their share while their presence (and thus the capacity share) in the market is negligible in 2013. Figure 2.20 illustrates this trend of mobile data traffic expected by 2017 as forecasted by Cisco Visual Networking Indexing (VNI).

It is obvious that existing spectrum for wireless and mobile communication will not be sufficient to satisfy the upcoming requirements. And worse, the traditional approach of re-purposing spectrum of other applications (such as TV Broadcast spectrum) to become exclusively licensed spectrum is reaching its limits. In the US, the National Broadband Plan [39] outlines requirements for 500 MHz of new mobile and wireless spectrum below 6 GHz by 2020. In Europe, the European Parliament and Council approved the first Radio Spectrum Policy Programme (RSPP) [40] with the concrete action that the European Commission together with all Member States will ensure that "*at least 1200 MHz spectrum are*
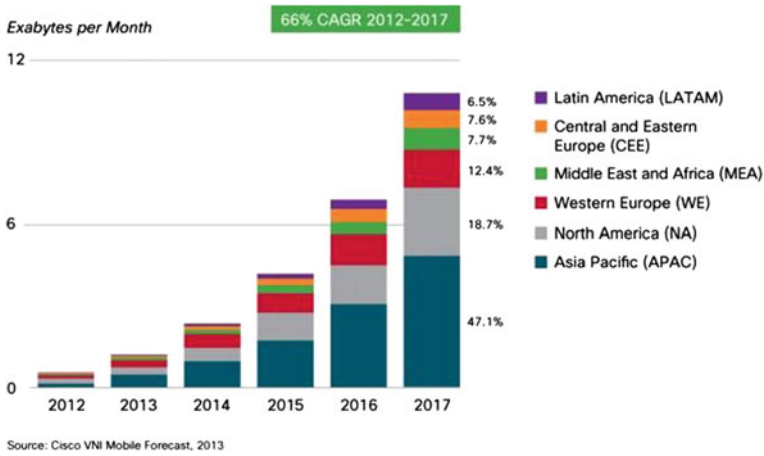
Exabytes per Month

66% CAGR 2012-2017

12

6

0

2012  2013  2014  2015  2016  2017

Latin America (LATAM) — 6.5%
Central and Eastern Europe (CEE) — 7.6%
Middle East and Africa (MEA) — 7.7%
Western Europe (WE) — 12.4%
North America (NA) — 18.7%
Asia Pacific (APAC) — 47.1%

Source: Cisco VNI Mobile Forecast, 2013

**Fig. 2.20** Mobile data traffic expected by 2017—Cisco Visual Networking Indexing

*identified to address increasing demand for wireless data traffic; and assessing the need for additional harmonised spectrum bands*".

The industry is therefore considering feasible alternatives with a specific focus on:

- Small Cells;
- Use of bands above 6 GHz for short-range extensions of existing systems;
- Spectrum Sharing;
- Heterogeneous Networks.

The approaches of Small Cells and millimetre wave bands above 3 GHz rely on traditional thinking: the Small Cells idea is to reduce the cell sizes of Base Stations and Access Points such that the number of users per cell, Base Station and/or Access Point is reduced. As a result, the available spectrum is split over a reduced number of users and thus there is more capacity available to each user. In the mmWave approach, new frequency bands at 60 GHz or above are added to the existing mobile and wireless bands which are typically located below 6 GHz. Due to their high path loss characteristics, mmWave Base Stations and Access Points are complementing existing cellular infrastructure with high capacity, local cells of reduced size.

The Spectrum Sharing and Heterogeneous Networks approaches, on the other hand, rely on CR solutions as they have been extensively studied for over 10 years—large European Research Programmes such as IST-E$^2$R [41], IST-E$^2$R II [42] and ICT-E$^3$ [43] have substantially contributed to their development. A report of SCF Associates for the European Commission on "*Perspectives on the value of shared spectrum access—Final Report for the European Commission*" [44] has indeed identified for a given Scenario ("*Scenario 3*") a "*new spectrum capacity available from sharing*" of "*400 MHz*". Related standardization is actively driven in various SDOs including IEEE DySPAN with a focus on

Dynamic Spectrum Access (DSA) solutions and ETSI Reconfigurable Radio Systems Technical Committee (ETSI RRS) on Licensed Shared Access (LSA) [45] in 2.3–2.4 GHz and TV White Space (TVWS) secondary access in 470–790 MHz (see more on this in Sect. 1.3). DSA solutions are expected to play a role in the mid- to long-term since the inherent highly dynamic spectrum access characteristics are still uncertain from an economic and business feasibility perspective. LSA targets a rather short- to mid-term implementation building on static or quasi-static approaches which is supported by political and regulation activities—the European Commission has indeed issued a Standardization Mandate (EC Mandate M/512 [46] with a specific request to develop LSA standards with support from CEPT Working Group Frequency Management (CEPT WG FM) which develops the regulation framework for enabling an implementation of LSA in Europe in Project Teams PT52 [47] and PT53 [48]. Due to its immediate relevance, LSA will be discussed in further detail in the sequel.

Finally, the Heterogeneous Networks approach considers solutions for enabling the user Mobile Devices to exploit the entire available Radio Framework. Indeed, why shouldn't a Mobile Device exploit all available Radio Access Technologies (RATs) supported by the underlying modem platform? Even a simultaneous operation of multiple distinct RATs is possible with suitable solutions being proposed by IEEE 1900.4 [49] and other standards.

In the following, the current LSA activities are presented in further detail as an example for an upcoming implementation of CR in Europe.

### 2.6.2 Licensed Shared Access as a Use Case for Realizing CR

LSA is a technology enabling the secondary usage of spectrum based on a long-term license agreement between an LSA Licensee (typically a Cellular Operator) and an Incumbent (e.g. public safety). The European Commission's *Radio Spectrum Policy Group* (RSPG) currently defines LSA as follows [50]:

> A regulatory approach aiming to facilitate the introduction of radiocommunication systems operated by a limited number of licensees under an individual licensing regime in a frequency band already assigned or expected to be assigned to one or more incumbent users. Under the LSA framework, the additional users are allowed to use the spectrum (or part of the spectrum) in accordance with sharing rules included in their rights of use of spectrum, thereby allowing all the authorized users, including incumbents, to provide a certain QoS.

The licensing approach in combination with static or quasi-static availability of shared bands leads to a guaranteed level of Quality of Service (QoS) and a business case which is far more straightforward and obvious compared to the highly dynamic DSA case.

Indeed, LSA can provide additional resources to mobile operators and economic incentives to governments even if it is used for relatively static and long term spectrum sharing. Figures 2.21, 2.22, 2.23 illustrate the differences between the traditional, exclusively licensed, LSA and DSA based approaches. It becomes obvious that LSA will improve the exploitation of spectrum resources in the short- to mid-term but a quasi-optimum exploitation is expected to require a more dynamic DSA approach in the long term despite the technical, economic and business feasibility hurdles.

As mentioned previously, the European Commission has recently issued EC Mandate M/512 with a specific request to develop Standards enabling the implementation of LSA in Europe. ETSI is working on corresponding solutions in the ETSI RRS Technical Committee and has issued a first deliverable which details the intended first implementation in Europe in the 2.3–2.4 GHz band [51]. This band corresponds to 3GPP LTE Band 40 which was first made available to cellular communication in China. Thanks to this fact, the latest generations of Mobile Devices support this mode and are thus inherently "*LSA ready*" in the 2.3–2.4 GHz band – under the assumption, of course, that no further features are required in the Mobile Devices and the access to LSA bands is managed from the Network Infrastructure side. The high-level system design proposed by ETSI is further illustrated in Fig. 2.24. In this context, two new functions are introduced into the wireless and mobile ecosystem:

- The LSA Repository (that constitutes a geo-location database) interacts with Incumbents in order to gain information on LSA band availabilities and access conditions for LSA Licensees;
- The LSA Controller access the LSA Repository in order to derive LSA Spectrum access requirements for LSA Licensees. Typically, the LSA Controller interfaces with the network infrastructure via the cellular operators' OA&M system.

Building on the upper high-level, conceptual presentation of LSA, ETSI RRS currently further develops the LSA system specification. The definition of System Requirements is currently on-going in ETSI TS 103 154: *System requirements for LSA in 2300–2400 MHz* [52]. This activity is expected to be followed by the detailed definition of an LSA System Architecture and finally the definition of related interfaces.

In parallel to ETSI standardization activities, CEPT WG FM is working towards ensuring the readiness of LSA introduction to the market from a regulation perspective. Indeed, two project teams are developing deliverables with the following scope:

- **CEPT WG FM PT52 [47]**: "… The Project Team shall: develop a draft ECC Decision, aimed at harmonising implementation measures for MFCN (including broadband wireless access systems) in the frequency band 2300-2400 MHz…"
- **CEPT WG FM PT53 [48]**: "… The Project Team shall handle the following tasks: … Develop an ECC Report on general conditions, including possible
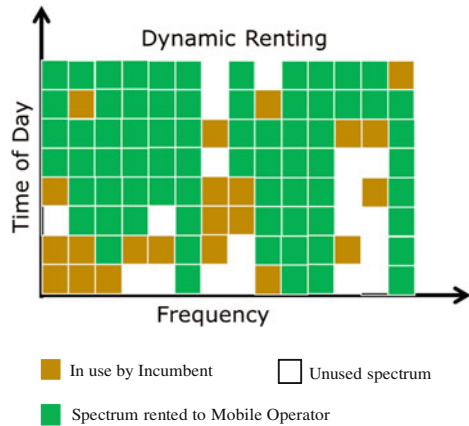
**Fig. 2.21** Illustration—
usage of spectrum capacity
without spectrum sharing
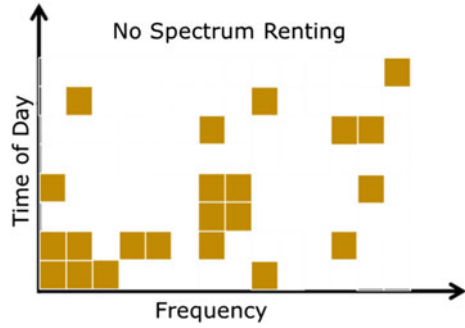
**Fig. 2.22** Illustration—
usage of spectrum capacity
with licensed shared access
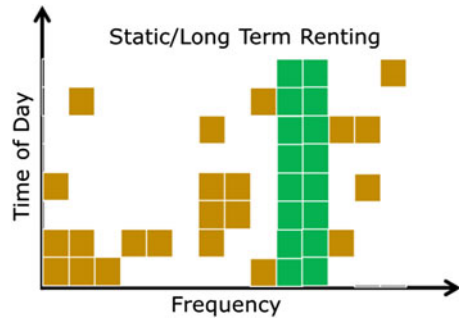
**Fig. 2.23** Illustration—
usage of spectrum capacity
with DSA

sharing arrangements and band-specific (if not dealt with by a specific project
team) conditions for the implementation of the LSA that could be used as
guidelines for CEPT administrations.…" A corresponding ECC Report is about
to be finalized under the title "ECC Report 205: Licensed Shared Access
(LSA)".
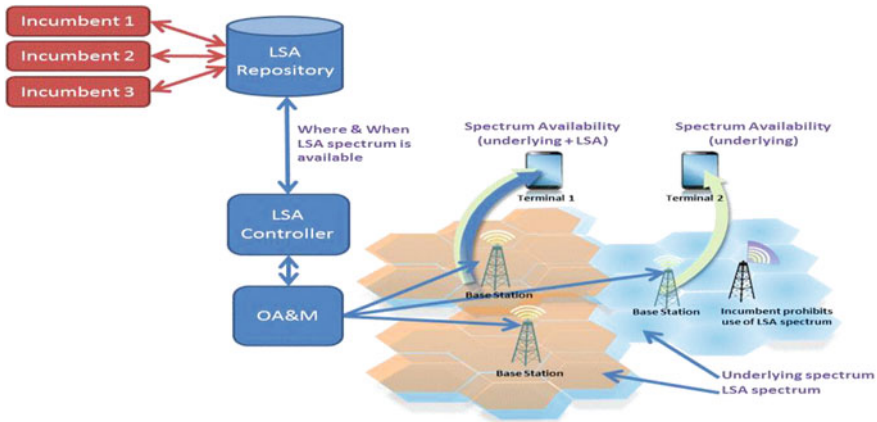
**Fig. 2.24** Illustration of the licensed shared access approach [51]

The development of LSA is thus a brilliant example for an efficient interaction of the European Commission, CEPT and ETSI driving the introduction of a new technology to the market.

### 2.6.3 Conclusions

As a result of extensive research in the field of CR over more than 10 years, the technology is finally reaching market readiness, in particular with the imminent market introduction of LSA in Europe in the 2.3–2.4 GHz band. One reason of this late adoption of the technology is due to the complex interrelations between concerned stakeholders and the disruptive economic and business considerations. Investment in network infrastructure is only justified if there are guarantees on available mobile and wireless spectrum capacity—this simple fact still represents a key hurdle for further CR solutions which become mature from a technical perspective.

## 2.7 Scenario Planning Methodology[1]

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[1] Dirk-Oliver von der Emden: the views expressed here are solely those of the author in his private capacity, and do not necessarily reflect the views of OFCOM.

This section outlines ideas for the application of scenario planning methodology to the realm of CR. It first reviews some basic principles involved with scenario planning. Then it proceeds with discussing possible avenues for classification and categorization of CR concepts as well as their inherent features in terms of enablers for or obstacles to their development. Such analysis would be helpful to better structure and organise the scenario planning. To conclude, the section outlines a particular methodology proposal for delineation of CR deployment scenarios, supported by an example of high-level scenario planning for the future evolution of CR.

## 2.7.1 Role and Benefits of Scenario Planning

As commercial CR applications begin to appear, it is required to back them with techno-economic modelling as means of proving economic viability of CR technology in various use cases. This could assist both in discovering of the profitable business models for CR as well as informing policy makers on shaping of regulatory regimes for radio spectrum access that would be favourable for CR innovation while not impairing on existing spectrum uses and users [53].

However before being able to conduct the meaningful techno-economic analyses, first it is important to understand and chart the general directions of possible evolutions of respective business opportunities. Obviously, this is not a trivial question in the case of as yet unproven CR technology, which until now existed mostly in the research labs or a few non-commercial pilots. So it is important to identify the general questions as to how and into which directions the overall development of CR will progress, before embarking on more detailed levels of operational planning and business forecasting.

It is in such instances of seeking broader views on overall trends and likely developmental paths of particular business and market segments, where the methodology of "scenario planning" comes into view [54–57].

In general, the essence and flow of scenario planning may be described by the following steps:

(1) Depicting sequences of events as *stories* that explain how we get from today to some future outcomes:

(a) what are present-day trends and influences?
(b) which forces may influence the evolution of the story?
(c) can the events be categorised as "highly likely", "uncertain", or "highly unlikely"?
(d) any events qualifying as milestones? I.e. would they have a decisive impact on directing overall development towards one specific outcome (with other words: must they happen or must they not happen if one or several outcomes is/are to occur)?
(e) attainability, desirability of particular outcomes?

(2) Identifying interactions between the scenarios, i.e. co-existence and/or relative progress of the scenarios:

(a) analysis of the linkages between events in order to identify the enablers and hurdles that will influence the relative speed of development of each scenario;

(3) Ensuring consistency and plausibility of scenarios through iterations:

(a) development of an integrated picture of the future, using elements of the identified scenarios.

(4) Based on the generated scenarios, outlining strategy options and developing most optimum strategy in order to achieve objectives.

Today several methods for building scenarios are known, such as the *Intuitive Logics* (IL), *Probabilistic Modified Trends* (PMT) and "*La Prospective*" [54]. Applied to the realm of CR business forecasting, perhaps the IL would be the most conducive methodology in comparison with the two other ones because of its inherent proclivity to addressing essential features of any CR planning exercise:

- absence of quantifiable historical data to characterise the development of future scenarios;
- the equal probability or, in other words, uniform uncertainty of the developed scenarios;
- orientation towards the learning and improved understanding of the involved processes rather than the reliability of the end products—the scenarios itself.

It is suggested [54] that while the inherent flexibility of IL method allows applying it in a broad variety of situations, the more deterministically oriented nature of PMT and "La Prospective" methods makes them optimal for use in "once-only problem solving" type of applications. In the case of evolving CR technology we would be interested in the long-term anticipative exploratory analysis, which thus naturally lends itself to the domain of IL [53].

Nevertheless, it is possible and sometimes useful bridging the differences between IL methodology and deterministic scenario planning of PMT kind, such as may be seen embodied by the Schoemaker's school of scenario planning [58]. Examples of recent works bringing the latter types of scenarios into the field of CR may be found in [56]. This bridging between the IL and PMT/Schoemaker's methods may be done by building the IL-derived scenarios along the clearly identifiable and quantifiable axes of uncertainty factors. This allows the clear identification of the most influencing factors and their analysis in order to discuss strategic development directions. Moreover, it gives the ability to detect warning signals as regards anticipated future developments once (one of) the identified uncertainties become more certain and/or certain milestone had been passed.

In the following subsections we shall address the issue of categorisation of CR with reference to its spectrum access modes, followed by the identification of respective enablers and hurdles for future development. This analysis would be helpful in carrying out the first steps of scenario planning.

### 2.7.2 Categorisation of CR Spectrum Access Modes

If CR is considered as disposing of user-independent intelligence, one possible approach when establishing a catalogue of CR employing Dynamic Spectrum Access (DSA) methods is to categorize the CR devices/networks according to the features of their "decision-making" processes with respect to spectrum access and usage mode. This decision making may be concerned with answering many questions such as "when" (moment & duration), "where" (location), "how" (frequency band, modulation, etc.), at which cost/price, etc. With this logic in mind, the Fig. 2.25 below proposes a categorisation of CR use with regards to spectrum access behaviour.

It is believed that these categories are not mutually exclusive. Actually, it may be presumed that many CR devices/networks will certainly have the ability to display several of such behaviours thanks to their inherent flexibility and re-configurability.

Examples as to how some presently envisaged CR deployment models relate to these three categories:

- Category A: master–slave;
- Category B: ad-hoc/mesh networks;
- Category C: autonomously sensing and deciding devices.

For instance, if a CR system intends to employ a Cognitive Pilot Channel (CPC), the category (or categories) retained to characterise the system will depend on the functionalities and features of the CPC [59].

### 2.7.3 Identification of Associated "Hurdles" and "Enablers"

It is proposed to develop a "matrix" for the identification of obstacles to and stimuli for the uptake and proliferation of CR in relation with the categories identified above. This identification has many similarities with the PEST analysis [56], however, the point here is really to propose identifying certain specific multi-dimensional axes for the Political-Economic-Societal-Technological (PEST) type analysis. An example of such matrix for identifying obstacles and enablers is offered below in Fig. 2.26.

It is proposed here to consider three categories of enablers/drivers (there may be others, or the categorization may be different), which may be identified as follows:

- "Technical enabler": (future) technological achievements, which will drive, give further incentive to research, development, production and exploitation of CR technology;

**Fig. 2.25** Categorisation of CR use inspired by "spectrum use scenarios" in ETSI TR 102 802 [37]
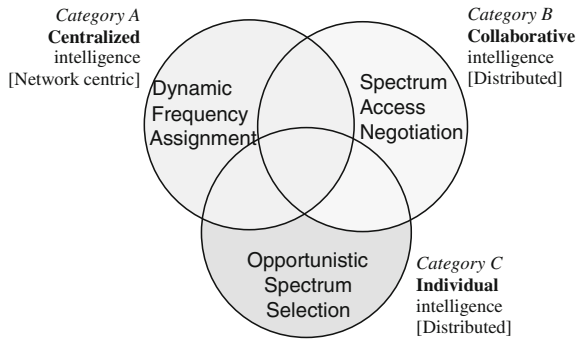


- "Socio-economic enabler": social and/or economic factors that are incentives for the uptake and/or adoption of CR technology;
- "Regulatory enabler": regulatory measures, such as removal of some existing regulations, or enactment of some new ones, both of which acts would create incentives for investments in and/or adoption of CR technology.

Some examples for enablers[2] are given in the following Table 2.5.

The enablers, as well as hurdles, eventually identified as relevant for one CR category must not necessarily be relevant for another one. The relevance needs to be examined on a case-by-case basis.

In a similar vein, below the three categories of hurdles are proposed (and again, there may be others, or the categorization may be different), which may be identified as follows:

- "Technical hurdle": engineering challenges in relation to CR, whose solutions are not conceivable for production on a large industrial scale in the short to medium term;
- "Socio-economic hurdle": social and/or economic factors that inhibit the production and/or adoption of CR;
- "Regulatory hurdles": pieces of (present-day) regulation, compliance to which is disproportionately costly or inhibit uptake of CR concepts.

Some examples of hurdles for CR development are offered in the following Table 2.6.

Not surprisingly, it may be noted that the number of hurdles that spring to mind is larger than the number of enablers. The issue of balancing the situation by promoting incentives for CR innovation will be addressed later in this book.

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[2] Some examples were taken from [60], noting that in this reference the drivers are associated with radiocommunications applications ("markets") that are more specific than the categories discussed in this section.
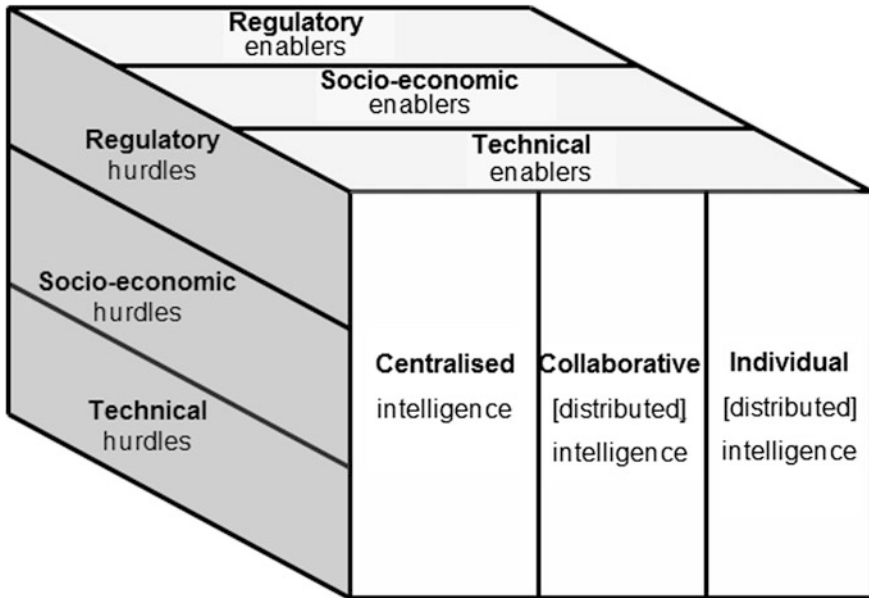
**Fig. 2.26** Matrix of enablers and hurdles for CR implementation

**Table 2.5** Examples of CR enablers

| Enablers | Type |
|---|---|
| Simplified post sale service and bug fixing | Technical |
| Easier upgrade routes and clear path of migration to newer SDR based platform | Technical |
| Access to more waveforms | Technical |
| Potential for lower development cost due to more generic hardware platform and more flexible software architectures | Economic |
| Deregulation in the field of formal requirements when marketing R&TTE products | Regulatory |

## 2.7.4 Importance of CR Scenario Planning for Radio Spectrum Management

The scenario-based approach could clearly assist in better understanding of realities and perspectives of CR evolution and proceeding towards developing a comprehensive techno-economic regulatory framework of radio spectrum access rules for CR/SDR-based wireless applications.[3]

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[3] It has been recognized that scenarios were of considerable value in spectrum planning as they could provide useful insights into how spectrum management may be affected by future events having implications for demand for spectrum [61].

**Table 2.6** Examples of hurdles impending development of CR

| Hurdles | Type |
|---|---|
| Protection (e.g. detection) of incumbents spectrum users | Technical |
| Availability of CPUs: | Technical |
| • In replacement of nowadays ASICs | |
| Power consumption of mobile devices: | Technical |
| • Technology of electric accumulators (batteries) | |
| Irreversibility of allocation of spectrum to license-exempt CR operation | Economic |
| Transaction costs of "spectrum trades" | Economic |
| Spectrum and technology fragmentations: | Economic |
| • Unfavorable for amortization of non-recurring costs | |
| • Hinders emergence of economies of scale | |
| Inflexibility of provisions of primary radio licenses: | Regulatory |
| • Inhibition of spectrum trading | |

The key would be to analyse and clarify the identified technological, economic and regulatory hurdles and enablers impacting future evolutions of CR, which would become the basis for building scenarios of CR development. Paths within the scenarios will depend, amongst other things, on chronological order when the various barriers identified will be overcome or the enablers become effective.[4] In that regard it is worth giving special focus to regulatory aspects. Because the peculiar nature of the regulation is that its shortcomings (when identified) can be reduced or eliminated overnight, simply by the (political) will of the competent governmental authority responsible for its enactment. Thus regulation can easily be both a hurdle (if status quo with shortcomings is upheld) and enabler (adoption of corrective regulation), as illustrated in Fig. 2.27.

But when completed, the scenarios are likely to generate different outcomes in respect of the strength of the demand for additional spectrum for CR and/or requirement for modifications to the radio regulatory environments. Thus the regulatory establishment will be in itself affected by future evolutionary developments of CR, see Fig. 2.28.

In fact, it may be observed that it is only natural to expect that the regulation be adaptive to any developments of wireless technology, both before and after the take-off of CR. More discussion on the impact analysis is offered in Chap. 5 of this book.

At the end, an important result of scenario planning could be evaluations with respect to the need for additional and/or specific spectrum made available for CR, its timing, the assumptions concerning the need re-allocations of spectrum or the adoption of completely novel approaches to spectrum management.

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[4] Amongst other things, "there are differences between the scenarios in terms of the pace of change and the demand for additional spectrum" [57].
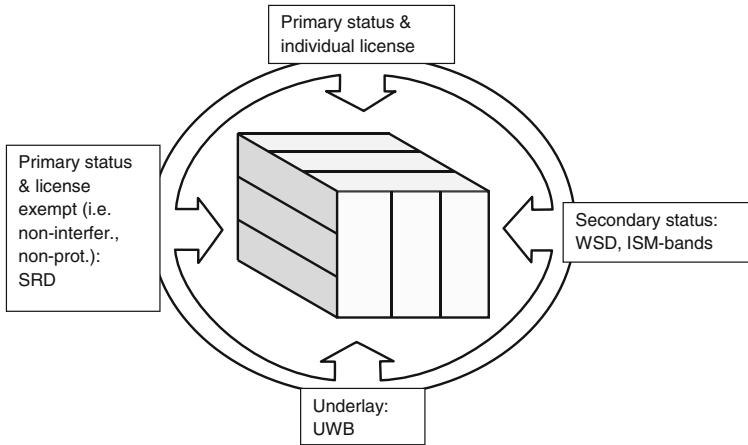
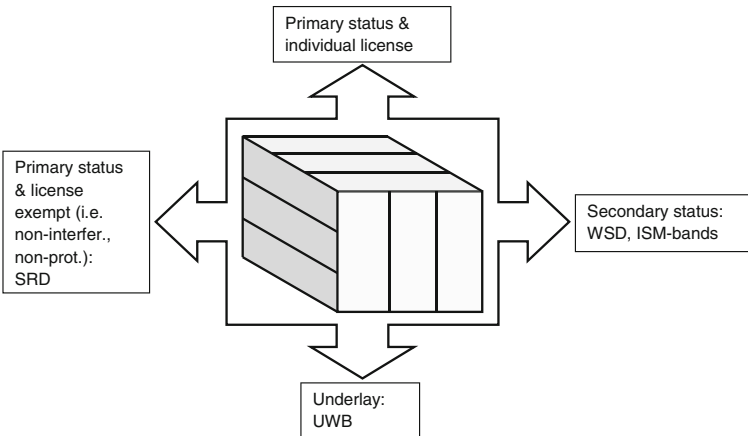**Fig. 2.27** The regulation as impacting factor of CR development



**Fig. 2.28** CR development scenarios affecting the future regulations

## 2.7.5 *Example of Scenario Planning for CR as DSA Technology*

In this subsection we discuss scenarios for CR-based DSA market development. These scenarios were developed with the highest conceivable level of abstraction, in order to provide a broad look at possible directions for future development of CR technologies as business-changing technological innovation. Innovation is an important defining element in this context as it refers to the practical implementation of the new technology rather than solely theoretical understanding.
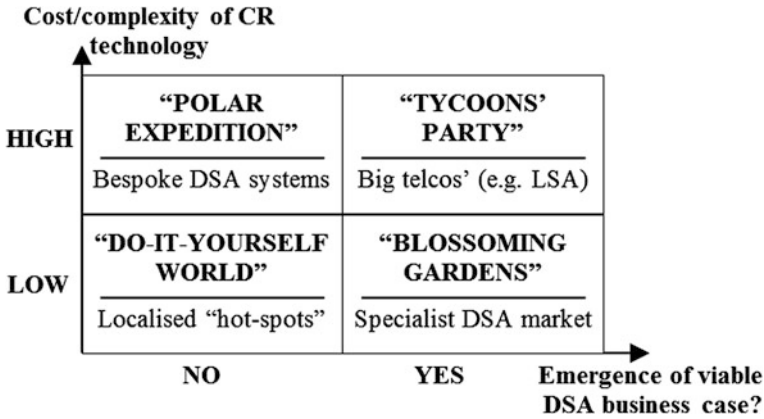
Fig. 2.29 Example of high-level scenarios for CR-based DSA business, adapted from [53]

It is thus proposed to build the high-level scenarios with reference to two most prominent uncertainties of CR-based DSA applications, namely:

- resolving the challenge of technical complexity of CR DSA technology, and
- finding a viable business proposition for DSA applications.

These two uncertainties are offered as top uncertainties affecting the pace of development of CR technologies with reference to both an intuitive logic (the IL method) and some real-life developmental facts. The first uncertainty is backed by the observation that, as of today, a solid commercially available prototype DSA application is still to appear. And as regards the second point, it may be surmised that the absence of significant industry efforts in promoting the CR DSA applications, seem to suggest that industry is, as yet, is not convinced there is any real revenue generating viable business case in exploiting of DSA concepts.

By accepting the identified uncertainties as defining axes for building scenarios for future evolution of CR-based DSA business, the four scenarios could be mapped accordingly against those uncertainties, as illustrated in Fig. 2.29.

Of the proposed four scenarios, the "Polar Expedition" appears to represent the current status quo, where the business prospects are uncertain and technological complexity is very high. Thus the name of scenario alluding to singular deployments of pilot systems, or military users with dedicated custom-built applications.

The "Tycoons' Party" scenario would represent the changing ecosystem characterised by appearance of clear business value proposition for DSA. Yet while the cost/complexity of CR technology would remain high, this scenario would likely to benefit a select few big players, be it large established telecommunications operators or some ambitious heavyweight newcomers such like Google. An obvious example springs to mind, namely that if and when the LSA concept is implemented, this would mean the industry transition into that scenario.

The "Blossoming Gardens" is an intriguing scenario whereas the falling costs and complexity of CR technologies would lower the barriers for market entry, while the DSA would be an attractive business proposition. This situation would be not unlike what happened with cellular mobile, which quickly turned from high complexity premium service technology to ubiquitous applications. So this previous example leads us to suggest that something similar would happen to CR DSA in such environment, whereas high profit margins would mean building certain "walls" that would keep the overall number of specialised players at some stable level.

On the other end, the "Do-It-Yourself World" scenario would represent the very different kind of developmental transition, with the CR technology becoming affordable, yet the business case for DSA remaining elusive. In such environment it could be envisaged that the CR DSA applications would spread out into a large number of local deployment islets, much like the Wi-Fi Hot Spots.

In summary it may be noted that the above example represents but example of very high-level considerations. Nevertheless, it already offers certain valuable insights and exploratory understanding of the environmental conditions steering the development of particular niche application of CR. Further insights might be obtained by applying such methodology in a more refined and multi-dimensional manner to analyse the various categories of issues discussed earlier in this section.

## 2.8 Taxonomy of CR Use Cases and Applications

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As shown in the preceding sections, there already exist many different CR deployment scenarios and their number constantly grows. These scenarios are being presented either as a description of different technological solutions or a set of business and use cases. To add to this somewhat bewildering picture, there also exist many definitions of CR itself. Thus the absence of a single classification system for the entire range of CR applications and use cases persists to this day. This brings to mind an "elephant in the room" metaphor, when blind men attempt to describe what they do not know by touching different parts of the colossus [62].

It seems important to start a discussion on definitions of CR and its applications by stepping back to the origins. The original  definition of CR has seen many alterations and derivations since it was coined by Mitola and Maguire back in 1999 [63–67]. All of those definitions, however, use various permutations of the three core features of CR: some kind of environmental awareness (such as spectrum sensing,

geolocation database, etc.), functional re-configurability, and "intelligent adaptive behavior" [65]. A comparative glossary of CR definitions is available in [65], p. 375.

The most formal definition of CR seems to be offered by ITU-R [68], and it will be assumed as a basis for further discussion here. The ITU-R sees CR as a system that employs technology allowing it: "*to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained*". It is important to note that such a definition avoids the issue of purpose of all those functionalities and adaptive operation, so it appears to be "application-agnostic".

On the matter of CR applications, the original vision postulated at least four use cases [63]:

- Spectrum pooling;
- Network management protocols;
- Personalised services delivery;
- Stability of type-certified downloads.

The ensuing decade of active R&D effort in this field again resulted in numerous alterations and expansion of that original vision. A good recent example of those alterations may be seen in an ITU-R report, being drafted at the time of writing this book, on the subject of CR use in land mobile services. It attempts to depict a dozen or so various CR applications from frequency agile autonomous systems to CR-assisted reconfiguration of user terminals for supporting heterogeneous radio access networks, see Sect. 2.1.

This not only illustrates the futility of fixing a complete definitive set of CR uses, it also shows intricate interlacing of CR methods and features at different layers of wireless technologies.

It might be argued that this absence of a clear and homogeneous classification of CR applications contributes to the protracted ambiguity with the standard definitions of CR and inhibits efficient codification of CR innovation ideas. To address this shortcoming, below a single universal taxonomy of CR use cases and applications is described.

It is proposed to start by considering two separate yet complementary planes on which the development of CR could be mapped. One plane would be based on the applications (utility) and the other one on a set of fundamental CR technical features to be implemented. The end target is a fully inclusive classification framework that is compatible with the need to adhere to the regulatory reality (through the description of the application hence allowing the link to underlying rules) and technological capabilities which must be satisfied to achieve the application. It is important that such an ultimate single taxonomy is broad and flexible enough as to also include possibility of future expansion by adding as-yet unknown prospective CR use-cases.
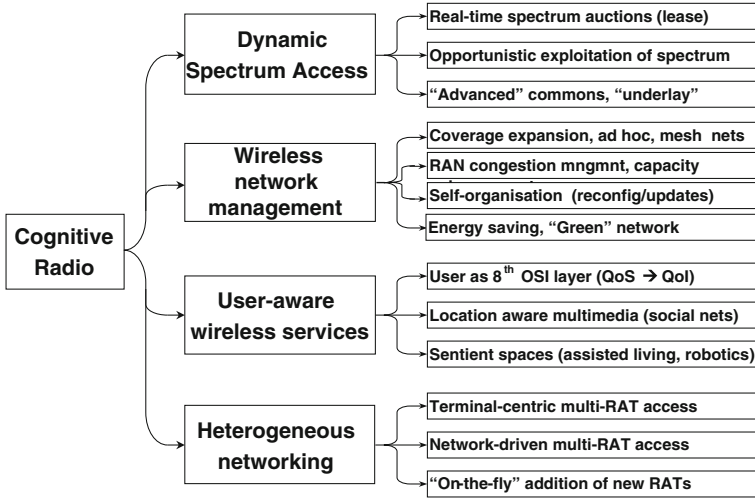
**Fig. 2.30** CR utility strands in the application plane

Within the application plane, the various strands of CR evolution could be defined by considering the distinctive utility functions of various applications. This is the same dimension as used originally by Mitola [63] to describe the envisaged set of CR use scenarios. This seems to be held valid today and in the future, as it does not have hard limit on the number of distinct utility strands, nor their length or degree of branching. Another important aspect of this utility plane is that the classification could be directly mapped to the radio spectrum access types and, hence, to spectrum regulations.

Figure 2.30 depicts the proposed outlook of the application plane of CR classification framework. It is based on initial branching of CR into four main utility classes-strands, broadly corresponding to the ones envisaged by Mitola [63]. Then, each of these strands may be branched again and again into sub-layers corresponding to the deeper degrees of utility differentiation for respective family of applications.

When looking at this figure it becomes obvious that only some (mostly one) of the possible CR development strands had seen sufficient attention and R&D activities. It is namely the DSA, which had stolen most of the lime light recently and shadowed other possible development strands. As a result, the other three strands had been seeing less or no attention from the CR research community. Granted, some of those alternative strands, such as heterogeneous networking or wireless network management, had seen significant developments. However mostly they grow from within the respective interest communities as incremental process innovations, without realising the bigger picture of relevance to the CR development.

It should be noted that the vision of application-plane CR taxonomy, as proposed in Fig. 2.30, accommodates well all types of CR use cases and applications

discussed elsewhere in this book and in the literature (e.g. sources quoted in this section). In fact, all of those different cases and applications could be mapped directly to one or another case-box in the proposed scheme [69]. But it may be also deduced that different authors may speak of cases in applications being on different levels (i.e. DSA application on level two vs. some more specific applications on level 3 or deeper). Such inadvertent de-focusing of discussion leads to the fuzziness and ambiguities of the aforementioned "elephant in the room" phenomenon.

When analysing the classification of CR applications offered in Fig. 2.30, it might be noted that this representation can be further enriched by bringing into view the additional angle of technology. The point here is that other than purely utilitarian functions performed by a given CR device or network, it would also be useful to consider at which technological capability they could operate. Here it is worth reminding that all CR technology rests on several fundamental premises (essentially, technological abilities), i.e., having awareness of the radio environment, and being able to adapt radio parameters based on that environment, with or without the cognition aspect. So, the technical capabilities represented in the taxonomy should take into account these key elements of the CR. Following this approach, it may be therefore assumed that the root of the technology path comprises of the four core features: radio information detection, radio parameter adaptation, learning and re-orientation. This is illustrated in Fig. 2.31 as four evolutionary levels of CR development in technological plane.

This figure helps to convey a simple message that it is unrealistic to expect all-singing-all-dancing CR applications to appear at once. To the contrary, it is likely that fully technologically capable CR applications will be developed through a gradual phased implementation. So it is logical to speak of 1st generation CR (such as TV White Space devices, for instance) and so on.

Inside each generational phase a further micro-classification might evolve by delving into more detailed aspects of the realised technical capabilities, such as specifying the types of radio awareness (e.g. autonomous sensing methods vs. Geolocation databases, etc., including their combinations), the allowed range of parameter adaptations (e.g. frequency ranges covered, modulations that can be achieved, or perhaps pre-defined full RATs), the learning means (e.g. reinforcement learning, artificial neural networks), etc. This might be taken down to the levels of highest resolution necessary to allow complete specification of the CR requirements. However these levels of details are not shown in Fig. 2.31 to keep it illustrational and conceptually simple.

While it is proposed to differentiate classification of CR uses in two separate planes, it may be also noted that in most cases they will be complementary whereas any given CR use case or application may be and should be characterised through combination of the utility and technology aspects. It is therefore suggested that such combined dual characterisation is essential in order to avoid confusion and ambiguity in specifying any past or future CR uses and applications. Once established, such classification system would by itself provide important practical value and uses, as discussed further.
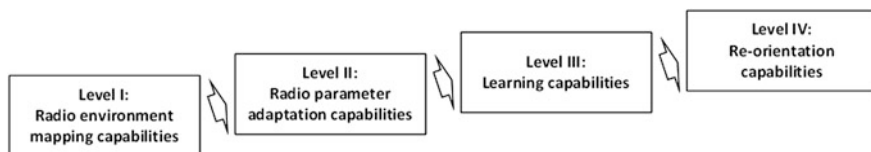
**Fig. 2.31** CR technology evolution path

One important practical aspect of having a universal taxonomy would be its contribution to the codification of information on CR use cases and applications, which is being constantly produced by numerous R&D efforts. More specifically, the accepted taxonomy should make possible unambiguous classification within an information structure that devices/networks could use (communicate to each other) to understand which forms of CR are already used in given area and, as relevant, which other forms can be used based on observation of any regulatory constraints and technical capabilities of the devices that are going to communicate.

A practical implementation of this concept would be to use the taxonomy tree as a basis for "genetic" codification of CR applications. For instance, taking the application-driven scheme proposed in Fig. 2.30 as a reference, each branch at a given level could be described by letters A, B, C, and so on. Then each application class could be described by the unique "genetic code-word" where the position and value of each letter define the respectively branching level and particular branch. For example, GDB-based white space devices could be described as belonging to CR class "A-B-B-A", see Fig. 2.32, whereas Terminal-centric Multi-RAT CR device could be defined as belonging to class "D-A", and so on.

An important inherent feature of such genetic codification would be its unlimited growth in terms of number of branching levels by simple extension of code-word, and the possibility to accommodate new future branching at certain levels by adding new letters at given position in the code-word.

The same principle of "genetic coding" could be applied to the technology-driven classification illustrated in Fig. 2.31 if each respective generational level (and further detailed internal branching) is given the appropriate code-letters. Then any conceivable CR application and use case could be uniquely defined by a combination of "application" and "technology" class codes.

An illustration of why this is important and how it may be used in practice is illustrated below in Fig. 2.33.

As shown in the illustration, other than providing explicit referencing, such codification might be useful for future automation of CR operations, such as being used as part of the necessary peer recognition algorithms and the processes for CR "frequency rendezvous".

In conclusion, this section outlined a uniform system for comprehensive classification of all conceivable CR use cases and applications by using two planes: applications and technology. Such broad taxonomic view allows characterising specific CR applications and placing them contextually on the overall big picture of various strands and generations of CR development.
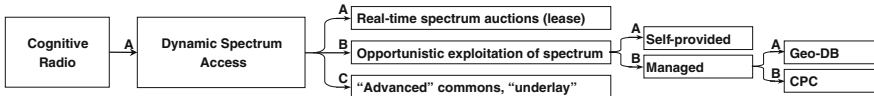
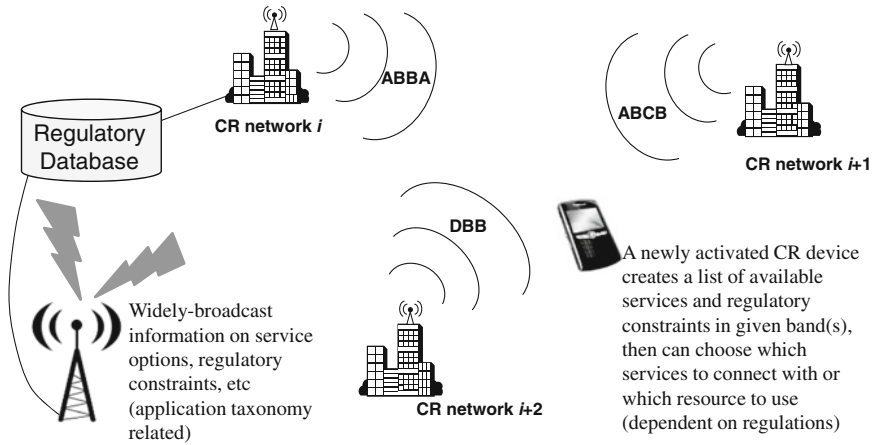**Fig. 2.32** Example of codifying a specific CR application



**Fig. 2.33** Illustration of using application type coding for CR rendezvous

More specifically, it may be observed that up to now, the popular association of CR solely with OSA/DSA utility concepts is in fact a misconception, as it puts a shadow on several other equally important strands of development of CR technology and applications.

An important practical effect of having a single universal taxonomy would be its contribution to the codification of information on CR use cases and applications.

## 2.9 EN 301 598: A European Harmonised Standard for Deployment of TV White Space Devices

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### 2.9.1 Introduction

The European regulatory regime for the use of wireless devices was designed some time ago with the aim of removing the need for national type approval of devices. In this regime, manufacturers who wish to place equipment on the European

market are required to self-declare conformance to the "essential requirements" of the Radio and Telecommunications Terminal Equipment (R&TTE) Directive. Such self-declaration can be achieved via a number of routes.

The primary route is through compliance with harmonized standards developed by European standards organizations. Harmonized standards that address the requirements of Article 3.2 of the R&TTE Directive (effective use of the spectrum to avoid harmful interference) are usually produced by ETSI. These typically include radio frequency (RF) requirements such as limits on radiated wanted and unwanted powers.

The European harmonized standard EN 301 598 [70] has recently been developed by ETSI committee BRAN to address white space devices operating in the UHF TV band. EN 301 598 is different from past harmonized standards for other bands, in that it includes many requirements which relate to control functionalities—in addition to the more traditional RF requirements. This is because unlike other radio devices, the regulatory limits on the RF characteristics (e.g. radiated signal frequency and power) of white space devices are not fixed and cannot be hard-coded into the device, but are rather communicated to the device by a database. Consequently, in addition to the usual RF requirements found in other standards, EN 301 598 specifies a number of control and monitoring functions (along with the relevant compliance tests) to ensure that WSDs behave in accordance with the regulatory parameters set out by databases. In this section we describe some of the key elements of the harmonized standard.

### 2.9.2 Masters, Slaves and Databases

As illustrated in Fig. 2.34, the specifications in EN 301 598 are based on a framework for access to TV white spaces (TVWSs) which involves the following four entities (see also the compatible UK framework described in Sect. 1.5.2 ):

(1) White space databases (WSDBs)—provide location-specific and device-specific information on TVWS availability (as well as other instructions) to white space devices (WSDs);
(2) WSDB web-listing—identifies the WSDBs that are approved by a given national regulatory authority (NRA) to provide service in the relevant jurisdiction;
(3)  Master WSDs—geolocated radio devices that are capable of accessing a web-listing, and directly communicate with a WSDB (via means other than the UHF TV band);
(4) Slave WSDs—radio devices that do not communicate directly with a WSDB, but operate subject to the control of a master WSD.

WSDBs and WSDs are required to exchange the following parameter sets in order for WSDBs to determine and communicate the available TVWS radio resource to the WSDs:
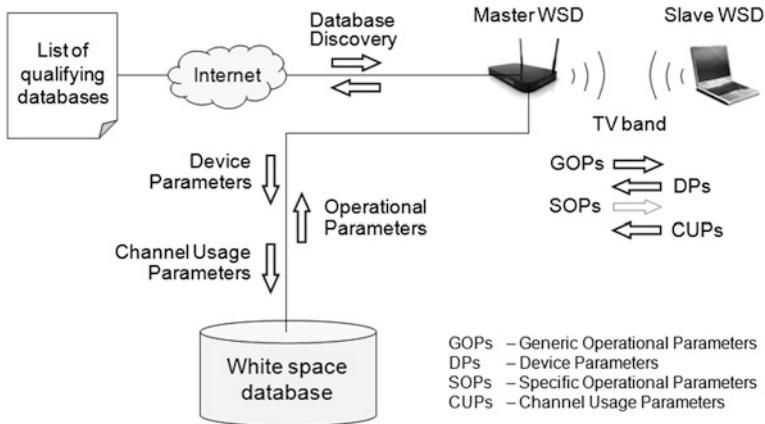
**Fig. 2.34** Framework for access to TV white spaces

(a) Device Parameters»CPöThese are parameters that are communicated from a
    WSD to a WSDB, and identify specific characteristics of the WSD. These
    include WSD location (and location uncertainty), type (A/B), category (mas-
    ter/slave), unique ID, technology ID, emission mask class, emission mask
    enhancements, and reverse intermodulation enhancements.
(b) Operational Parameters»CPöThese parameters are generated by a WSDB and
    communicated to WSDs. They specify the TV channels that a WSD can use,
    the emission limits in each channel, and a number of other ancillary param-
    eters. There are two types of Operational Parameters:

    • Specific Operational Parameters, and
    • Generic Operational Parameters.

    Specific Operational Parameters are specific to an individual WSD, while
    Generic Operational Parameters apply to all slave WSDs that are served by a
    particular master WSD. A WSDB communicates Generic Operational
    Parameters to a master WSD, which in turn broadcasts these to all slave WSDs
    in its coverage area. The Generic Operational Parameters account for certain
    characteristics of the serving master WSD (e.g. location, power, and hence
    coverage area), but assume default values for the Device Parameters of the
    slave WSDs.

(c) Channel Usage Parameters—These parameters are reported by a WSD to
    inform a WSDB of the *actual* radio resources that are used by the WSDs.
    These include the indices of the TV channels used and the emission levels in
    each channel.

## 2.9.3 The Operation of a White Space Device

Here we set out the sequence of procedures considered by EN 301 598 for the exchange of information between WSDBs, master WSDs, and slave WSDs. These procedures reflect the following three high level regulatory requirements:

(1) A WSD must only operate in compliance with the Operational Parameters provided by a WSDB that is approved by the relevant national regulatory authority.
(2) A WSDB must receive certain essential information (Device Parameters) from a WSD in order to generate and communicate Operational Parameters to that WSD.
(3) A WSDB must maintain a record of the actual usage of the TV white spaces. To this end, each WSD must report back to the WSDB the actual digital terrestrial TV (DTT) channels and the powers that it uses.

Requirement (3) arises from a need for a cautious approach to the deployment of WSDs. Specifically, the circumstances for secondary use in the UHF TV band—namely the widespread primary use of the band, and the new paradigm of radio resource allocation by WSDBs—mean that the impact of interference must be managed carefully, making it important for regulators to be able to monitor the use of TV white spaces. For this reason, it is required that WSDBs collect detailed information about TVWS usage.

A typical sequence of procedures may be described in the context of four separate phases A to D as presented next, and illustrated in Fig. 2.35. The Specifications in EN 301 598 are not prescriptive in relation to these four phases and, in practice, different wireless technologies may implement these in a variety of ways so long as the necessary information is exchanged correctly and WSDs radiate in the UHF TV band subject to the correct Operational Parameters.

### 2.9.3.1 Phase A: Specific Operational Parameters for a Master WSD

Phase A relates to the generation and communication of Specific Operational Parameters for master WSDs, and involves the following steps:

(1) The master WSD must access a list of approved WSDBs via the internet. This web-list may be hosted by the relevant national regulatory authority (as is the case in the UK) or by a trusted party;
(2) The master WSD will then select a WSDB from the list, and request Specific Operational Parameters from the WSDB for its own transmissions. In this process, the master WSD must first communicate its Device Parameters (including its location) to the WSDB;
(3) The WSDB will then generate the Specific Operational Parameters that the master WSD must comply with for its transmissions. To perform this, the WSDB will use a) the Device Parameters provided by the master WSD, and b)

DP: Device Parameter
SOP: Specific Operational Parameter
GOP: Generic Operational Parameter
CUP: Channel Usage Parameter
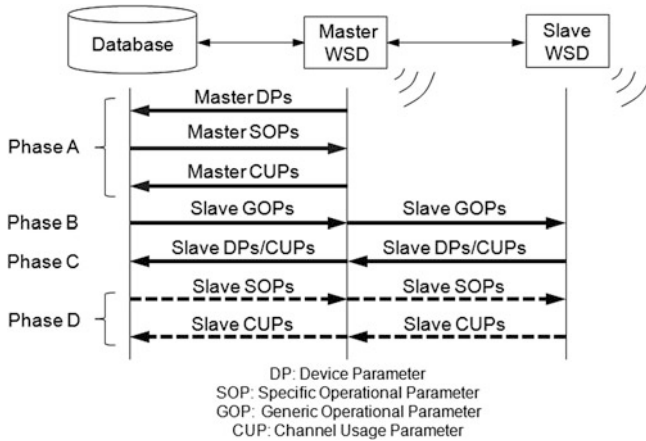
**Fig. 2.35** Illustration of operational phases

TVWS "availability data" which it holds, and which indicate the maximum power that a WSD is permitted to radiate within each DTT channel at a particular location in order to ensure a low probability of harmful interference to the incumbent primary users. The WSDB will communicate the Specific Operational Parameters to the master WSD;

(4) The master WSD must communicate back to the WSDB the actual channels and powers which it intends to use (its Channel Usage Parameters). These usage parameters are likely to be different from the Specific Operational Parameters provided by the WSDB. This is because the master WSD may not be capable of transmitting in all DTT channels indicated by the WSDB, or at the channel-specific emission limits, or there may be a network control function that restricts the emissions of several master WSDs to ensure that they do not interfere with each other;

(5) The master WSD can then start transmissions in the UHF TV band according to its reported Channel Usage Parameters.

### 2.9.3.2 Phase B: Generic Operational Parameters for Slave WSDs

Phase B relates to the generation and communication of Generic Operational Parameters. These parameters describe the DTT channels and maximum powers that any slave WSD within the coverage area of a given master WSD can use for its transmissions.

Generic Operational Parameters primarily describe the radio resources that a slave WSD may use in order to associate with a master WSD. We use the term "association" to refer to the process whereby a slave WSD initially identifies itself to its serving master WSD. This is a usual process in many wireless technologies.

A networked element—the base station or access point—broadcasts information to indicate to the non-networked elements—the terminals—the radio resources (typically frequencies) that the latter may use in order to identify themselves to the network and to request further access to the medium. In the case of TV white spaces, it is envisaged that (following association) some technologies will continue to use the radio resources specified by the Generic Operational Parameters for on-going transmission of data, while other technologies will only use these as a means to submit a subsequent request for additional radio resources (see phase D). Phase B involves the following steps:

(1) The master WSD must contact the serving WSDB and request Generic Operational Parameters for the transmissions of any slave WSDs that might be located within its coverage area.
(2) The WSDB will then use the TVWS "availability data" and the information that it holds about the master WSD (see Phase A) to calculate the master's coverage area. The WSDB will then calculate the Generic Operational Parameters by assuming (a) that slaves may be at any location within the master's coverage area, and (b) default conservative values for the Device Parameters of the slaves. Note that at this stage no slave Device Parameters are available at the master WSD or at the WSDB. This is because no slave WSDs will have yet associated with the master WSD. The WSDB will communicate the Generic Operational Parameters to the master WSD.
(3) The master WSD must then broadcast the Generic Operational Parameters to slave WSDs within its coverage area. The actual Generic Operational Parameters broadcasted will normally be a subset of those communicated by the WSDB, and may even correspond to a single channel only. This is because the master WSD may not be able (or willing) to receive transmissions from slave WSDs in all the channels identified by the WSDB.
(4) Slave WSDs must comply with the channel-specific powers limits specified in the broadcasted Generic Operational Parameters when they transmit in the UHF TV band for purposes of association with the master WSD.

### 2.9.3.3 Phase C: Association of a Slave WSD with a Serving Master WSD

Phase C relates to the association of slave WSDs with master WSDs. Any slave WSD wishing to transmit in the UHF TV band, must undertake the following:

(1) A slave WSD must associate with a master WSD by identifying itself to the master. A slave WSD may submit its full set of Device Parameters for this purpose.
(2) To perform the above, the slave WSD must transmit in compliance with the Generic Operational Parameters broadcasted to it by the master WSD.
(3) The master WSD must forward the identities, or the full set of Data Parameters, of its associated slave WSDs to the WSDB.

(4) Slave WSDs which have already associated with a master WSD may continue to use Generic Operational Parameters for subsequent transmissions. Alternatively, they may request Specific Operational Parameters in order to benefit from increased TVWS availability (see Phase D).

### 2.9.3.4 Phase D: Specific Operational Parameters for a Slave WSD

Phase D relates to the generation and communication of Specific Operational Parameters for individual slave WSDs. Specific Operational Parameters describe radio resource availability that is greater than that described by Generic Operational Parameters. This is because, absent the required data, WSDBs make cautious assumptions regarding the Device Parameters of slave WSDs when they generate Generic Operational Parameters, and these results in somewhat restrictive radio resources in terms of available DTT channels and channel-specific emission limits. A slave WSD that is able to accurately determine its location or whose Device Parameters are more favourable than those assumed by the WSDBs in generating Generic Operational Parameters (e.g. cleaner spectrum emission masks), will be able to gain access to greater radio resources if it communicates its Device Parameters to a WSDB in order to receive Specific Operational Parameters. The above is described as phase D and involves the following steps:

(1) A slave WSD will provide its Device Parameters to its serving master WSD and request Specific Operational Parameters. The master WSD will forward this request to the WSDB. An alternative implementation may be one where the Device Parameters of the slave WSDs reside in the master WSD, and it is the master WSD which requests Specific Operational Parameters for the slave WSDs from the WSDB;

(2) The WSDB will generate Specific Operational Parameters by using the TVWS "availability data" that it holds and the slave Device Parameters provided by the master WSD;

(3) The WSDB will communicate the Specific Operational Parameters for a slave WSD to the master WSD. The master WSD will then communicate the Specific Operational Parameters to the associated slave WSD;

(4) The slave WSD will communicate to the master WSDB the actual channels and powers that it intends to use (its Channel Usage Parameters). The DTT channels described by the Channel Usage Parameters may be a subset of those identified by the Specific Operational Parameters. By definition, the powers described by the Channel Usage Parameters must be lower than the emission limits specified by the Specific Operational Parameters. The master WSD will forward the Channel Usage Parameters to the WSDB. An alternative here is that all intelligence resides in the master WSD, in which case the master makes decisions on behalf of the slave WSD regarding the channel(s) and powers(s) to be used by the slave, and the master itself generates the Channel Usage Parameters on behalf of the slave.

## 2.9.4 Requirements and Specifications

The requirements in EN 301 598 are intended to mitigate harmful interference by ensuring that the wanted emissions (inside the band) and unwanted emissions (both inside and outside the band) do not exceed specific limits. The limits outside the UHF TV band are specified in EN 301 598 in the same manner as existing harmonized standards, and include limits on Tx/Rx spurious emissions and transmitter inter-modulation. On the other hand, the limits inside the UHF TV band are specified in a novel way. This is for two reasons:

(a) A WSD may operate in a single DTT channel, or it may operate simultaneously in a mixture of contiguous and non-contiguous DTT channels.
(b) The limits on the wanted emissions are not fixed, but are location-specific, channel-specific, and are specified by a WSDB.

Given the above, the specifications in EN 301 598 are divided in two groups: namely RF requirements and control/monitoring requirements. The latter ensure that the WSDs communicate the necessary Device Parameters to a WSDB, and that they operate in compliance with the Operational Parameters that they receive from the WSDB. EN 301 598 requires that the Device Parameters, Operational Parameters, and Channel Usage Parameters include a minimum set of information. Their detailed specification (such as the format and size of the data) is mostly up to design of the WSD-WSDB protocols (via proprietary, *de facto*, or industry-defined standards such as IETF PAWS). The requirements are summarized below.

### 2.9.4.1 Nominal Channel

A Nominal Channel is defined as one or more contiguous DTT channels that are used by a WSD for its wanted transmissions. Its lower and upper edge frequencies must coincide with the European harmonized DTT channel raster ($470 + 8k - 1$ and $470 + 8k$ MHz, respectively). The bandwidth of a Nominal Channel (and indeed the total bandwidth of wanted emissions) must not exceed the value specified by the WSDB.

### 2.9.4.2 In-Block Power and Power Spectral Density

The total radiated in-block RF power of a WSD must not exceed a specified level $P$. In the case of WSD operation in a single DTT channel, the value of $P$ is equal to $P_1$ in dBm/(8 MHz) as communicated by the WSDB for that channel. In the case of simultaneous operation in multiple DTT channels, the value of $P$ must be the lowest of the $P_1$ values in dBm/(8 MHz) specified for each of the channels being used. The radiated in-block RF power spectral density of a WSD within any DTT channel must not exceed a level $P_0$ dBm/(100 kHz) as specified by the WSDB for that DTT channel.

### 2.9.4.3 Emission Masks Inside the UHF TV Band

EN 301 598 specifies a total of five spectrum emission masks (or *classes*) inside the UHF TV band. The manufacturer must declare the emission class with which the WSD complies. Class 1 devices have the most stringent emission mask and will benefit from increased TVWS availability.

### 2.9.4.4 Database Discovery

At start up, and before initiating any transmissions, a master WSD must locate and consult a web-listing of approved WSDBs relevant to its geographical domain. A Master WSD must not transmit if it cannot consult a web-listing. Furthermore, a master WSD must not request Operational Parameters from a WSDB that is not on the web-list.

### 2.9.4.5 Master and Slave Updates

It may be necessary in certain circumstances (e.g. to protect incumbent primary users) to instruct a WSD to cease transmissions within a short time interval. As a result, there is a requirement that master WSDs must support an update function, through which a WSDB can inform that the Operational Parameters of the master WSD and its served slave WSDs are no longer valid. For this, a master WSD must either a) be able to receive an update from the WSDB within $T_{Update}$ seconds (push update), or b) send an update request to the WSDB every $T_{Update}$ seconds (pull update). A master WSD must support a minimum $T_{Update}$ value of 60. A master WSD must cease transmission, and must instruct the slaves attached to it to cease transmission, if it receives an update from the WSDB that the relevant Operational Parameters are no longer valid. The actual value of $T_{Update}$ will be specified by the relevant national regulatory authority and communicated to the WSDs by the WSDBs.

Similar requirements apply to slave WSDs, but here the update interval is fixed. A slave WSD must cease transmission within 1 s when updated to do so by its serving master WSD. Furthermore, a slave must cease transmission within 5 s of discovering that it can no longer receive updates from its serving master WSD.

### 2.9.4.6 Loss of Connection with the Database

A master WSD must at all times be reachable by a WSDB within a time interval $T_{Update}$ (via pull or push update). However, this will not be possible if the connection with the WSDB is lost. In such cases, the master WSD must cease transmissions, and instruct its associated slave WSDs to also cease transmissions.

#### 2.9.4.7  Geolocation

A key element in the operation of WSDs is the ability of the WSDB to provide Operational Parameters on the basis of the location of the WSD. However, not all WSDs are required to geolocate. For example, the broad location of slave WSDs can be derived from an estimate the coverage area of the serving master WSD. WSDs which do geolocate, however, must observe certain requirements. A WSD, whose location is more than a defined threshold distance away from the location it reported for obtaining Operational Parameters, must stop using those Operational Parameters. This threshold is itself an Operation Parameter, and its value can be set by the national regulatory authority. Furthermore, a geolocated WSD must check its location at least every 60 s.

#### 2.9.4.8  Device Types

EN 301 598 defines two types of WSDs. Type A WSDs are intended for fixed use only, and can have integral, dedicated or external antennas. Type B WSDs are not intended for fixed use and can have an integral or a dedicated antenna. The requirement for an integral or dedicated antenna is to mitigate the risk of users tampering with the antenna.

#### 2.9.4.9  User Access Restrictions and Security Measures

An important concern from the perspective of interference to incumbent primary services is the risk of users tampering with the WSDs. If a WSD user is capable of bypassing the process of receiving Operational Parameters from a WSDB, or is capable of inputting bogus Operational Parameters into the WSD, then serious interference could result. For this reason, EN 301 598 contains strict requirements to prevent users from modifying the configuration of the WSD, and to ensure that communications with a WSDB are secured and authenticated.

### 2.9.5  Conclusions

Database-assisted operation of white space devices in the UHF TV band is an example of a new paradigm in spectrum management, and relies on the real-time communication of regulatory emission limits and instructions to the wireless devices. However, just like other wireless devices, in order to be placed on the European market a white space device must comply with the Radio and Tele-communications Terminal Equipment (R&TTE) Directive.

EN 301 598 has been produced by ETSI as a harmonized standard for white space devices in the UHF TV band as a means to prove compliance with the requirements of the R&TTE Directive. It contains a number of traditional

requirements, such as restrictions on emission masks, as well as many new requirements to account for database-assisted operation.

Since the database-assisted approach to spectrum management is still in its infancy, the current version of EN 301 598 is quite likely to be revised as white space technologies develop, and as regulators, manufacturers and users gather information on the operation of these devices in the field.

One area in particular where we expect to see further development relates to the issue of interference among TV white space devices. Mitigation of such interference can be achieved in a variety of ways, for instance by databases taking on a coordination role, or by means of polite protocols implemented by the devices themselves. At this stage it is too early to include requirements for such mitigation techniques in the harmonized standard—as the number of TV white space devices in the field is likely to remain low in the short term—but such requirements may become increasingly necessary as usage of TV white spaces becomes widespread.

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