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Technical Report

Electromagnetic compatibility and Radio spectrum Matters (ERM); Operation methods and principles for spectrum access systems for PMSE technologies and the guarantee of a high sound production quality on selected frequencies utilising cognitive interference mitigation techniques

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Foreword

This Technical Report (TR) has been produced by ETSI Technical Committee Electromagnetic compatibility and Radio spectrum Matters (ERM).

A future ETSI Technical Specification on the recommended spectrum access technique in the present document is planned as well as tests on a demonstrator built to the specifications in the TS. An ETSI Technical Report on the defined RF compliance tests carried out on the demonstrator for the selected spectrum access mechanism defined in the TS is planned to be prepared.

Please note that although the technology demonstrator will concentrate on one particular application, the technology will ultimately be transferable to other PMSE applications.

Introduction

Radio microphone devices use 100 % duty cycle to convey voice or music either for a live event such as concerts and theatres or for a recorded event such as the production of film and television programs. Interference during this process is not only commercially disastrous; it can be also harmful to the audience where a public address system is in use.

The regulations governing the operation of PMSE (Program Making and Special Events) systems are currently in flux in Europe. During the process of changeover compression of the television channels is taking place below 790 MHz. The spectrum between 790 MHz and 862 MHz has been considered a Digital Dividend and allocated for use by Electronic Communications Networks. This has resulted in a reduction of spectrum available for PSME.

Protection

PMSE devices use very low radiated power levels (the maximum PWMS RF power level is 50 mW) in comparison to most other radio communication systems. In order for them to function properly, they are protected from interference. Up to now this has not been a problem since PMSE equipment operated in locally unused TV channels that presented a very predictable RF environment. In the future, many different kinds of new devices, the characteristics of which are difficult to fully anticipate at this time, may be sharing this space. Some of these devices will be used for broadband data, and will occupy any spectrum which is available to them, i.e. from a few MHz to a multiple of 10 MHz. Other uses of the Digital Dividend, which may eventually go down to 600 MHz, are use by the emergency services and other mobile services.

The question of how to protect PMSE equipment from interference caused by new devices has been the subject of much discussion and debate. Traditionally, incompatible radio communications systems were assigned to operate in separate frequency bands, but this scheme is becoming impractical in today's world of intensive spectrum use. A more dynamic and robust solution is needed.

Spectrum efficiency

Including cognitive techniques into a PMSE system has a high potential for increasing spectrum efficiency. It has to be investigated which cognitive techniques are suitable and how they need to be modified to serve the needs of the PMSE system.

Flexibility of spectrum access

Including cognitive techniques into a PMSE system has a high potential for increasing the flexibility of spectrum access. It has to be investigated which cognitive techniques are suitable and how they need to be modified to serve the PMSE systems needs.

1 Scope

The present document analyses the various possible techniques for spectrum access systems for PMSE technologies and for the guarantee of a high sound production quality on selected frequencies utilising cognitive interference mitigation techniques and recommends a specific method.

2 References

References are either specific (identified by date of publication and/or edition number or version number) or non-specific. For specific references, only the cited version applies. For non-specific references, the latest version of the reference document (including any amendments) applies.

Referenced documents which are not found to be publicly available in the expected location might be found at http://docbox.etsi.org/Reference.

NOTE: While any hyperlinks included in this clause were valid at the time of publication ETSI cannot guarantee their long term validity.

2.1 Normative references

The following referenced documents are necessary for the application of the present document.

Not applicable.

2.2 Informative references

The following referenced documents are not necessary for the application of the present document but they assist the user with regard to a particular subject area.

[i.1] ETSI TR 102 683 (V1.1.1): "Reconfigurable Radio Systems (RRS); Cognitive Pilot Channel (CPC)".

[i.2] Li, Y., Quang, T. T., Kawahara, Y., Asami, T., and Kusunoki, M. 2009. Building a spectrum map for future cognitive radio technology. In Proceedings of the 2009 ACM Workshop on Cognitive Radio Networks (Beijing, China, September 21 - 21, 2009). CoRoNet '09. ACM, New York, NY, 1-6.

[i.3] WiMAX Forum Spectrum and Regulatory Database.

NOTE: http://www.wimaxforum.org/resources/wimax-forum-spectrum-and-regulatory-database

[i.4] TEDDI database.

NOTE: http://webapp.etsi.org/Teddi/

[i.5] ETSI EN 300 422 (V1.3.2): "Electromagnetic compatibility and Radio spectrum Matters (ERM); Wireless microphones in the 25 MHz to 3 GHz frequency range".

[i.6] ETSI TR 102 546 (V1.1.1): "Electromagnetic compatibility and Radio spectrum Matters (ERM); Technical characteristics for Professional Wireless Microphone Systems (PWMS); System Reference Document".

[i.7] ERC Recommendation 70-03 (2009): "Relating to the use of Short Range Devices (SRD) PWMS: Annex 10 + Annex 13".

[i.8] CEPT Report 30: "Technical identification of common and minimal (least restrictive) technical conditions for 790 - 862 MHz for the digital dividend in the European Union".

[i.9] CEPT Report 32: "Recommendation on the best approach to ensure the continuation of existing Program Making and Special Events (PMSE) services operating in the UHF (470-862 MHz), including the assessment of the advantage of an EU-level approach".

[i.10] ETSI EN 300 726 (V7.0.2): "Digital cellular telecommunications system (Phase 2+) (GSM); Enhanced Full Rate (EFR) speech transcoding (GSM 06.60 version 7.0.2 Release 1998)".

[i.11] Draft ECC Report 147: "Additional compatibility studies relating to PWMS in the band 1518-1559 MHz excluding the band 1544-1545 MHz".

[i.12] OET Report, FCC/OET 08-TR-1005: "Evaluation of the Performance of Prototype TV-Band White Space Devices Phase II".

[i.13] ETSI TR 102 802: "Reconfigurable Radio Systems (RRS); Cognitive Radio System Concept".

3 Definitions and abbreviations

Further definitions can be found on Terms and Definitions Interactive Database (TEDDI) [i.4].

3.1 Definitions

For the purposes of the present document, the following terms and definitions apply:

Adaptive Modulation and Coding (AMC): protocol that sets modulation and coding parameters depending on channel state

Ask Before Talk (ABT): spectrum access protocol requiring a cognitive radio device to consult a local database, frequency coordinator or other authority before starting transmission

Cognitive PMSE system (C-PMSE): PMSE system, which includes a Cognitive Engine (CEN)

NOTE: See ITU definition CRS below. However adding the highlighted wording:

A radio system (optionally including multiple entities and network elements), which has the following capabilities:

- to obtain the knowledge of radio operational environment and established policies and to monitor usage patterns and users' needs;
- to dynamically, autonomously and whenever possible **proactively** adjust its operational parameters and protocols according to this knowledge in order to achieve predefined objectives, e.g. minimize a loss in performance or increase spectrum efficiency;
- and to learn from the results of its actions in order to further improve its performance

Cognitive Radio System (CRS): radio system (optionally including multiple entities and network elements), which has the following capabilities:

- to obtain the knowledge of radio operational environment and established policies and to monitor usage patterns and users' needs;
- to dynamically, autonomously and whenever possible adjust its operational parameters and protocols according to this knowledge in order to achieve predefined objectives, e.g. minimize a loss in performance or increase spectrum efficiency; and to learn from the results of its actions in order to further improve its performance

content plane: contains audio and/or video information, analogue or digital

NOTE: The term data plane/data channel is not used in the present document due to potential irritations. Instead signalling and content plane are used.

control plane: control data plane (contains control and management information)

Detect And Avoid (DAA): technology used to protect radio communication services by avoiding co-channel operation

NOTE: DAA operates as follows: before transmitting, a system senses the channel within its operative bandwidth in order to detect the possible presence of other systems. If another system is detected, the first system avoids the transmission until the detected system disappears.

Direct Mode: Mobile-to-Mobile communication

downlink: communication from master to slave

NOTE: The terms "Forward / Reverse Link" are not used in the present document due to potential irritations. Instead downlink and uplink are used.

Dynamic Frequency Allocation (DFA): protocol that allows for changing transmit frequency during operation

Dynamic Power Control (DPC): capability that enables the transmitter output power of a device to be adjusted during operation in accordance with its link budget requirements or other conditions

fixed: physically fixed, non- moving device

NOTE: includes temporary event installations as well.

infrastructure: nomadic entities

latency: time difference between input and output

NOTE: A professional audio system consists of many different devices such as loudspeakers, amplifiers, mixing desks, etc . The PMSE latency value discussed in the present document is defined as *analogue electric audio input to analogue electric audio output from one transmitting device to its receiving device.*

link adaptation: result of applying all of the control mechanisms used in Radio Resource Management to optimize the performance of the radio link

Listen Before Talk (LBT): spectrum access protocol requiring a cognitive radio to perform spectrum sensing before transmitting

location awareness: capability that allows a device to determine its location to a defined level of precision

master: unit which controls the radio resource changing actions

mobile: physically moving device

Professional Wireless Microphone System (PWMS): wireless microphones, IEM, audio links, etc.

Programme Making and Special Events (PMSE): production equipment, especially wireless equipment used by broadcasters, musical and theatrical shows, and others

radio environment map: integrated multi-domain database that characterizes the radio environment in which a cognitive radio system finds itself

NOTE: It may contain geographical information, available radio communication services, spectral regulations and policies, and locations and activities of collocated radios.

Service Level Agreement (SLA): defined level of service agreed between the contractor and the service provider

signalling plane: plane which contains only signalling information, e.g. Radio Resource commands, battery status, etc.

NOTE: The term data plane / data channel is not used in the present document due to potential irritations. Instead signalling and content plane are used.

slave: unit which performs the commanded actions by the Master

uplink: direction from Slave to Master

NOTE: The terms "Forward / Reverse Link" are not used in the present document due to potential irritations.

white space: label indicating a part of the spectrum, which is available for a radio communication application (service, system) at a given time in a given geographical area on a non-interfering / non-protected basis with regard to other services with a higher priority on a national basis

White Space Device (WSD) = TV Band Device (TVBD): cognitive devices proposed to work in the VHF / UHF-TV-Band

3.2 Abbreviations

For the purposes of the present document, the following abbreviations apply:

ABT	Ask Before Talk
AMC	Adaptive Modulation and Coding
AMCT	Adaptive Allocation Table
AMR	Adaptive Modulation Rate
AP	Access Point
BER	Bit Error Rate
CEN	Cognitive Engine
CPC	Cognitive Pilot Channel
cpi	inter cognitive PMSE interface
C-PMSE	Cognitive - Programme Making Special Event entity or system
CRS	Cognitive Radio System
CSI	Channel State Information
DAA	Detect And Avoid
DAT	Device Allocation Table
DEM	Device Manager
DFA	Dynamic Frequency Allocation
DIC	Diversity Interference Cancellation
DIP	Dual In-line Package
DPC	Dynamic Power Control
DTV	Digital TeleVision
DVB-T	Digital Video Broadcasting - Terrestrial
ECN	Electronic Communications Network
EFR	Enhance Full Rate
EIRP	Equivalent Isotropic Radiated Power
ENG	Electronic News Gathering
FAT	Frequency Allocation Table
FCC	Federal Communications Commission (U.S.)
fci	frequency coordinator interface
FCO	Frequency Coordinator
FDD	Frequency Duplex Division
FFT	Fast Fourier Transformation
FM	Frequency Modulation
GPS	Global Positioning System
GSM	Global System for Mobile Communications
GUI	Graphical User Interface
HMI	Human Machine Interface
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
ID	Identifier
IEM	In Ear Monitoring
IMD	Intermodulation Distortion
ISM	Industrial Scientific and Medical frequency band
LAN	Local Area Network
LBT	Listen before Talk
LTE	Long Term Evolution
MMI	Machine-to-Machine Interface
MRC	Maximum Ratio diversity Combining
MSS	Mobile Satellite Service
PAT	Power Allocation Table
PMO	Performance MOnitor

PMSE	Programme Making Special Events
PWMS	Professional Wireless Microphone System
QoS	Quality of Service
RAT	Radio Access Technologies
REM	Radio Environmental Map
RF	Radio Frequency
RFID	Radio Frequency Identifier
RMS	Root Mean Square
ROI	Return on Investment
RRM	Radio Resource Manager
RRS	Reconfigurable Radio System
RSS	Received Signal Strength
RSSI	Received Signal Strength Indication
sci	scanning receiver interface
SCR	Scanning Receiver
SINR	Signal to Interference and Noise Ratio
SLA	Service level Agreement
SLE	Service Level Entry
SLM	Service Level Monitor
SNR	Signal to Noise Ratio
SRD	Short Range Device
T-DAB	Terrestrial Digital Audio Broadcast
TEDDI	Terms and Definitions Interactive Database
TTI	Transmission Time Interval
TTV	Time To Violation
TVBD	Television Band Device
UHF	Ultra High Frequency
UMTS	Universal Mobile Telecommunication System
UWB	Ultra-Wideband
W-CDMA	Wideband - Code Division Multiple Access
WiMax	Worldwide Interoperability for Microwave access
WLAN	Wireless Local Area Network
WSD	White Space Device

4 Differences between mobile services and Professional Audio Transmission

4.1 General remarks

This clause compares the differences in the operation of mobile services and PMSE systems and the features implemented to meet those.

Mobile services technology is very advanced and has evolved dramatically over the last decade. Sophisticated advancements have been widely implemented and have become state of the art. Therefore it has been suggested that the PMSE market adopt features from the mobile world that have been widely accepted and proven as being very beneficial.

This clause comments on the specifics of PMSE systems and those of mobile services. It also comments on why features of mobile systems cannot be simply taken over one-to-one, and instead have to be adapted to the specifics of PMSE.

4.2 Comparisons in the operation of PSME against other mobile systems

PMSE systems are required to meet very high quality levels for audio transmission. This means e.g. audio bandwidths of more than 20 kHz and SNRs of more than 80 dB. Consider e.g. a typical CD recording based on 16 bit resolution, equal to 96 dB dynamic range. By contrast, for a simple voice telephone service 3 kHz audio bandwidth and SNRs in the range of 20 dB are sufficient. However, the most critical criterion is that short interruptions are not acceptable on PMSE, but can be tolerated on mobile systems. In moderate quality PMSE equipment, interruptions still have to be kept below approximately 1 ms.

In general, PMSE systems so far are designed under the objective of maximizing audio quality and ensuring that the quality levels are met 100 % of the time. In contrast to this, mobile systems are mainly designed under the objective of maximizing capacity/spectral efficiency and coverage.

Increasing the coverage of a base station means the investments for installing a network are lowered, as a smaller number of base stations are needed to cover a certain area.

Increasing the spectral efficiency of a system means that more traffic, either voice or data can be transferred in a given swath of spectrum. As a consequence, the service provider can earn more money and increase the return on investment (ROI) in spectrum licenses.

4.3 Latency

PSME systems require a maximum latency of 3 ms to 5 ms in order to maintain lip synchronisation. Unfortunately, existing and planned mobile communication systems cannot support this latency requirement.

Various techniques which can be considered cognitive are used within various short range devices; these include Listen Before Talk (LBT) and detect and avoid (DAA). Unfortunately these techniques allow a time gap before logging a new frequency. PWMS require continuous transmission in order to convey the full range of speech or music. Therefore these techniques are not suitable for PWMS usage.

4.4 Signalling between mobile and infrastructure equipment

PMSE devices are mainly unidirectional, whereas mobile phones are bidirectional. A wireless microphone on or behind stage cannot be advised remotely by a central network element to change RF parameters such as e.g. its frequency or its power during operation. Typically these parameters are fixed or can be configured by DIP-switches or menu settings by using an infrared interface. Planning for those parameters is done in advance of an event production.

The same applies for the other direction e.g. an in-ear monitor on or behind the stage. The receiver worn by an artist or actor typically cannot signal its actual receive quality to the in-ear-monitoring transmitter.

Back-channels are only partly implemented, mainly for battery supervision and power down of e.g. wireless microphones.

Another aspect is that PMSE devices typically cannot be identified. A wireless microphone does not transmit its ID, nor a training sequence or training symbols. Digitization would surely help here, but this comes at the cost of latency.

4.5 Link reliability

The main difference between PMSE and mobile service links is the link quality. For a high quality audio production, the high link quality objective has to be met 100 % of the time. In a mobile system, link quality varies over time and counteraction is taken on a sensed link quality degradation, so it is a reactive scheme. For PMSE a reactive scheme is not sufficient, which means that if an upcoming link degradation is predicted or even known, a counteraction has to be conducted in advance.

So far the need for ensuring a certain quality level 100 % of the time has led to the necessity to typically set PMSE operational parameters in a way that the highest audio quality can still be met even under the worst case. It is clear that this is a waste of radio resources; however the only way around this is that to know upcoming degradations well in advance. Proactive schemes are needed in contrast to reactive schemes as implemented in mobile services.

Interruptions of service are intolerable for high quality classes of PMSE. There is a 100 % duty cycle for PMSE, so there is no free time, no "quiet periods", which can be used to perform certain actions such as e.g. sensing by a PMSE device.

From the viewpoint of reliability of PMSE, the high audio quality also has to be ensured in critical scenarios such as objects being moved on the stage or the artist climbing between objects on stage, which is very common in theatre production. Because PMSE today contains no link adaption, those scenarios are being taken care of through applying enough fading margin in the link budget. A drop of a wireless link would lead to a stop of a production and therefore is not accepted.

In summary, a minimum specified service level has to be met under all circumstances, for 100 % of the time. However the required minimum service level may vary depending on whether a PMSE wireless device is used for a production with artists or a conference system. Therefore the quality requirement is a scalable parameter depending on the application.

4.6 Link quality

In figure 1, Comparison of reactive scheme of a mobile service and the newly proposed proactive scheme with C-PMSE is given. In mobile systems (solid line in figure 1), link quality is continuously monitored and supervised. Counteractions are triggered if the link quality falls below a certain quality threshold. In GSM, for example, a handover due to interference may be initiated.

However, as stated in clause 4.5, this is a reactive scheme, that does not comply with the requirement for high quality PMSE production (dashed line in figure 1), where the negotiated minimum service level has to be ensured for the entire time. Under no circumstances may the PMSE quality fall below the agreed quality threshold.

In summary, it can be said that in mobile, Radio Resource Management (RRM) is used to control the link parameters so that audio quality toggles around an average negotiated audio quality level, whereas in PMSE a certain quality level is maintained. The different objectives with the operation of PMSE and mobile systems is obvious. In a mobile system, the spectral efficiency is to be maximized whereas in PMSE a minimum service quality has to be ensured under all circumstances.

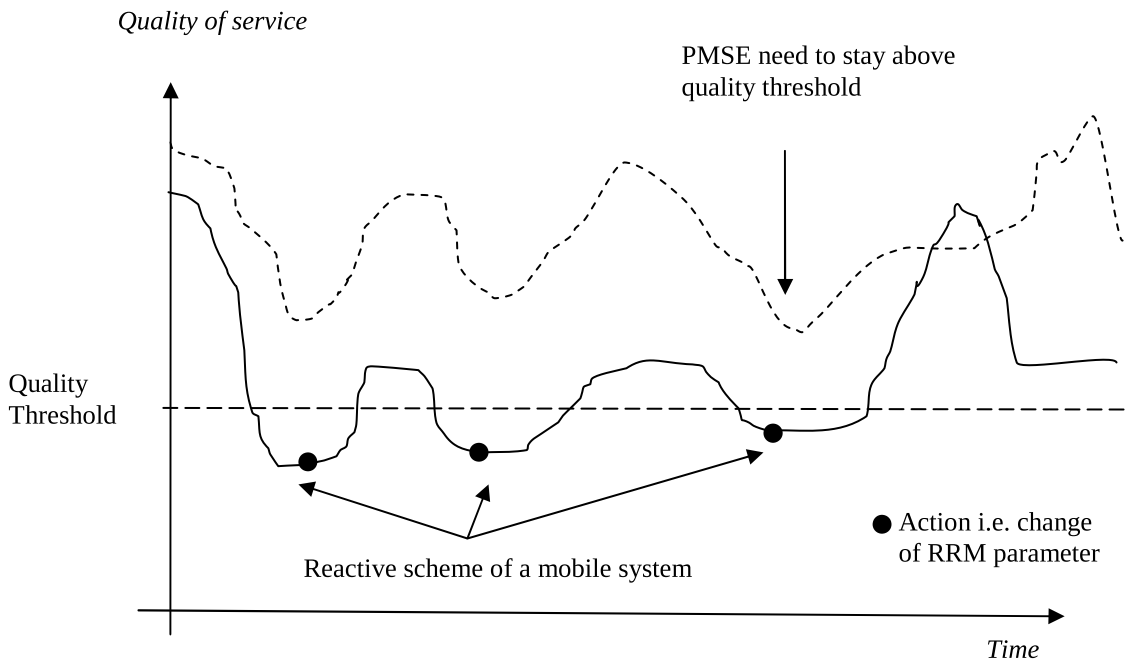

Figure 1: Comparison of reactive scheme of a mobile service and the newly proposed proactive scheme with C-PMSE

In a mobile system, link adaption is very advanced. In adaptive modulation rate (AMR) for instance, the robustness of the wireless link against interference can be traded against audio quality by using a variable audio codec. Higher audio compression will allow for heavier channel coding. Such schemes do not exist so far in PMSE. As stated above, a minimum service quality for PMSE has to be ensured under all circumstances, therefore degrading quality to ensure link reliability is not an option. With data services, adaptive modulation and coding are used to always get close to the Shannon Bound, which means that the data rate is maximized under the actually present SNR.

In analogue FM used with PMSE, given the tight latency constraints, so far no schemes do exist to trade off audio quality against actual SNR on the RF link.

4.7 Link Robustness

An analogue link such as FM with PMSE is much less robust than a digital link with tolerance to latency as used in mobile services. A short interfering pulse would cause an audible noise like a "click" on a PMSE link based on analogue FM. In a digital radio link, several adjacent symbols and thus many adjacent bits would also be distorted. However through interleaving/deinterleaving, distorted bits would be temporarily spread, of course at the expense of introducing latency. If multiple erroneous bits occur, however unbundled thanks to interleaving, the decoder can still reconstruct a perfect net bit stream because of redundancy. This is a fundamental difference between recovering an interfered analogue versus digital link. The reason, of course, is the real time nature of PMSE with latency below 4 ms.

4.8 Radio Resource Management (RRM)

Mobile systems typically incorporate a well advanced RRM. The use of spectrum in terms of frequency domain occupancy is e.g. set by switching on and off subcarriers in an OFDM system such as LTE. The use of spectrum in terms of time domain is e.g. explored in HSPA based on 2 ms Transmission Time Interval (TTIs). The use of spectrum in terms of code domain is e.g. done in W-CDMA/UMTS.

With analogue FM, this is hardly doable. The only free parameter would be the deviation. In a fixed channel bandwidth, the maximum audio frequency could be traded against deviation (Carson Bandwidth=2x max audio frequency +2x deviation). EN 300 422 [i.5] specifies multiple channel bandwidth ranging from 50 kHz up to 600 kHz. However, to dynamically adjust parameters such as channel bandwidth and deviation, appropriate signalling procedures are in place and what is even more important, a switch between different settings is click-free without interruptions of audio.

Frequency handover could solve some interference problems in dynamically changing PMSE scenarios, however a handover in frequency is click free and comply to non-audible interruptions (< 1 ms). It may also be necessary for a wireless microphone to contain two transmitter allowing y-connection, so as to establish two parallel wireless links for a limited time, as is common in most mobile systems.

Dynamic power control is not implemented in PMSE systems today. Static power control is partly available, e.g. a DIP-switch or menu in the wireless microphone can be used to set its output power. Dynamic power control would also require a back-channel, however that can be expected as a standard feature in the future, at least for high end PMSE microphones. Today, the static power control setting is set in such a way as to ensure that even under the worst case, the target audio quality level can be met. Obviously it is possible to increase efficiency by implementing dynamic power control.

Implementing power control in PMSE is not trivial for digital transmission. Typically transmission is not organized in frames, bursts or slots as interleavers or checksums are not implemented because they would introduce latency. Therefore a change in power would hit the constellation in the IQ Plane.

PMSE using analogue FM would probably be easy to manage in terms of power control as receivers typically use limiters to eliminate power variations. Limiters are of no problem as information is coded in the phase/frequency transitions. This requires a back channel with a very fast control loop.

4.9 Source Coding and Audio/Speech Compression

Mobile systems use heavy source coding, e.g. speech transcoding with GSM/UMTS [i.10]. By that, the amount of data to be transferred over a wireless link is significantly reduced. PMSE systems, although they are analogue, also use some sort of source coding. Multiband audio companders are used to reduce the dynamic range of the audio signal and by that the required SNR on the wireless link is also reduced.

4.10 Spectral Efficiency

In this clause we attempt to calculate spectral efficiency of PMSE, where the capability of the speech/audio compression technique is taken into account.

4.10.1 PMSE Calculation

The audio quality is assumed to have 100 dB dynamic range at an audio bandwidth of 20 kHz. The Shannon equivalent for this audio quality equals:

$$C = BW * ld\ (1 + S / N) = 20\ kHz * ld\ (1 + 10^{10}) = 660\ kbit/s.$$

The PWMS system reference document TR 102 546 [i.6] states that 20 MHz of spectrum supports 15 channels for an interference free operation.

Audio companders can reduce dynamic range by up to 50 dB. The Shannon equivalent after audio compression therefore is:

- $C = BW * ld\ (1 + S / N) = 20\ kHz * ld\ (1 + 10^5) = 330\ kbit/s.$
- Raw audio related spectral efficiency: 15 × 660 kbit/s / 20 MHz = 0,5 bit/s/Hz.
- Compressed audio related spectral efficiency: 15 × 330 kbit/s / 20 MHz = 0,25 bit/s/Hz.

4.10.2 Example

Table 1: Audio related spectral efficiency

	A Mobile System	PMSE
raw audio quality	8 kSa/s, 13 bit, 300 Hz to 3 400 Hz	100 dB, 20 Hz to 20 kHz
raw audio rate	104 kbit/s	660 kbit/s (Shannon equiv.)
compressed audio rate	12,2 kbit/s	330 kbit/s
channel arrangements	75 channels in 5 MHz	15 channels in 20 MHz
raw audio related spectral efficiency	1,56 bit/s/Hz	0,5 bit/s/Hz
compressed audio related spectral efficiency	0,18 bit/s/Hz	0,25 bit/s/Hz

From table 1, it can be concluded that related to the raw audio data, the spectral efficiency of a mobile system is 3 times better than that of PMSE, however if the compression technique is considered, it can be seen that PMSE does much better than a mobile system. This is a clear indication that a mobile system suffers from a lot of signalling overhead and that the compander technology used in PMSE is efficient.

4.11 Mobility

Mobile communication standards support high mobility. GSM900 for instance standardizes minimum performance for 250 km/h. In PMSE, similar requirements do exist. For instance, with the production for "Starlight express", artists drive at up to 15 m/s equal to 54 km/h.

4.12 Interference Scenarios

Interference scenarios significantly differ between PMSE and mobile systems. In a mobile system, the number of carriers from different links is low. In PMSE there may be events with 200 audio links simultaneously active. This creates a high risk for intermodulation products which desensitize receivers. This is especially the case in light of the fact that dynamic power control is not used. It also has to be considered that a mixing product goes down by 3 dB if the total power of the involved RF carriers goes down by 1 dB. Thus, power control would be of strong benefit.

Beside the intermodulation directly in receivers, reverse intermodulation is a serious effect on wireless microphones. In a scenario where two artists are standing next to each other, RF power may get into a wireless microphone backwards. Intermodulation products are generated and may hurt other wireless links. Sometimes artists also wear two transmitters e.g. for vocal and instrument, which are closely spaced.

4.13 Training and Channel Sounding

In digital systems, training sequences or training symbols are inserted that allow assessment of the characteristics of the channel. Also the SINR can be assessed from training. On analogue FM links as with PMSE, continuous monitoring of link quality is difficult. Often only received signal strength is monitored, which under no interference allows quantifying SNR; however in an interference constrained scenario, signal strength is not an appropriate measure. With digital links, Channel State Information (CSI) is continuously monitored which gives detailed insight into the actual SINR.

Beside monitoring radio link quality, training information with digital links is also very helpful on advanced receiver concepts such as Diversity Interference Cancellation (DIC) and Maximum Ratio Diversity Combining (MRC). The latter is more or less blind to interference while DIC can set the complex weights for combining in a way to maximize SINR.

Training information is a hook for distinguishing and separating users not available on analogue links.

4.14 Encryption

PMSE links with analogue FM transmission are unencrypted. Encryption is much easier on digital links. Conference systems therefore mostly use digital transmission. Also conference systems are less latency constrained, so delay introduced by digital conversion, coding and encryption is of less concern.

4.15 Coverage area

The coverage area seriously differs between PMSE and mobile service. The diameter of a cell of a mobile service may be up to 30 km or even more; however for PMSE it is typically 100 m line of sight.

4.16 Power Consumption on Mobile Device

Wireless microphones are under tough energy constraints; the minimum continuous operation time is 8 hours. They cannot profit from a low duty cycle of the transmitter as other mobile systems.

4.17 Characteristics of Wi-Fi versus PMSE and other mobile systems

Wi-Fi devices have more similarities with mobile systems than with PMSE in that Wi-Fi uses spectrum management and spectrum sharing techniques. Where PMSE devices typically are unidirectional, transmit only devices each Wi-Fi device is capable of both listening and talking in a half-duplex format. Wi-Fi's ability to listen to the medium allows for transmission scheduling and spectrum sharing. The technique used is actually referred to as Carrier Sense Multiple Access/ Collision Avoidance (CSMA/CA).

As a result of the half-duplex, CSMA/CA mechanism Wi-Fi there are pauses of transmission, which can be used for spectrum sensing purposes. Wi-Fi also uses Forward error correction and re-transmission mechanisms to ensure that over the air data transfer is robust. Furthermore, Wi-Fi uses rate adaptation such that as link quality decreases due to lost packets the radio adjusts the modulation and coding set to provide a better link margin. The natural consequence of this is a decrease in payload delivery rate.

Originally Wi-Fi was used for data file transfers between computers where "best effort" was acceptable. Wi-Fi links are now commonly used for both voice, music and video transfers. These transfers still use the same listen before talk protocol but use a series of higher speed packets to accomplish the transfer. When Wi-Fi is used to transfer isochronous traffic interruptions can become apparent and objectionable when the link quality drops significantly and the link quality mechanisms cannot fully compensate.

Even though some conference systems use also the ISM bands, these bands are unusable for wireless microphone systems with high QoS requirements.

5 Frequency Bands in consideration

5.1 Overview

Table 2 provides an overview of frequency bands listed in CEPT/ERC Recommendation 70-03 [i.7] in the annexes 10 and 13, PWMS and Audio Applications, as well as potential frequency bands as listed in CEPT Report 32 [i.9]. The following clauses provide further details on these frequency bands.

Table 2: Overview of frequency bands

Name	Frequency	CEPT/ERC Rec. 70-03 Annex 10, Annex 13	CEPT Report 32	Comments
Narrow band	29,7 MHz to 47 MHz	Yes	No	Not suitable for professional audio production.
VHF	174 MHz to 216 MHz	Yes	Yes	
UHF	470 MHz to 862 MHz	Yes	Yes	
Duplex Guard Band	821 MHz to 832 MHz	(Yes)	Yes	821 MHz to 832 is part of 470 MHz to 862 MHz
865 MHz	863 MHz to 865 MHz	Yes	Yes	Class 1 Harmonized Audio Band
L-Band, part 1	1 452 MHz to 1 477,5 MHz	No	Yes	Specific EU
L-Band, part 2	1 492 MHz to 1 518 MHz	No	No	Specific EU
L-Band, part 3	1 518 MHz to 1 559 MHz	No	No	Specific EU
1,8 GHz	1 785 MHz to 1 800 MHz	Yes	Yes	Specific EU
2,4 GHz	2 400 MHz to 2 483,5 MHz	No	No	ISM-Band, general SRD
5,8 GHz	5 725 MHz to 5 875 MHz	No	No	ISM-Band, general SRD

5.1.1 Narrow audio: 29,7 MHz to 47 MHz

Due its high noise level, long antenna length and restricted RF channel bandwidth of 50 kHz, this frequency band is not suitable for professional audio productions.

5.1.2 VHF: 174 MHz to 216 MHz

The VHF band was extensively used before the UHF band 470 MHz to 862 MHz was allocated as a tuning range. There is existing equipment in this band. However, there is an uncertainty about existing noise levels, e.g. man-made noise, which needs to be investigated before a final decision for this band can be made. PMSE is secondary user; the primary service in this band is broadcast distribution, e.g. DVB-T, T-DAB+, etc.

An enlargement of this band to 174 MHz to 233 MHz might be a fruitful area for investigation.

5.1.3 UHF: 470 MHz to 862 MHz

The UHF-TV frequency band is the spectrum with the heaviest use of PMSE systems. The upper part 790 MHz to 862 MHz has been allocated to new Electronic Communications Networks (ECN) services [i.8] and will not be available for PMSE from 2016 (or earlier) on (please see also clause 5.1.4). Therefore only the lower part of the current UHF-TV band, 470 MHz to 790 MHz, will be available in the future.

In addition, the Analysis Mason report (http://www.analysysmason.com/EC_digital_dividend_study) for the European Commission recommends further compacting broadcasting spectrum to at least 600 MHz; one Administration OFCOM UK (http://www.ofcom.org.uk/consult/condocs/600mhz_geographic/) is already consulting for the second time on the reallocation of this spectrum. Other services such as White Space Devices and the emergency services are also seeking allocations in the 470 MHz to 862 MHz band.

PMSE is secondary user to primary broadcast distribution services (e.g. DVB-T) in this frequency band.

5.1.4 Duplex Guard band: 821 MHz to 832 MHz

The Duplex Guard band is a potential EU harmonized band. Assuming that the channel plan as discussed in CEPT spectrum engineering groups is implemented Europe wide, there will be a FDD system with a duplex guard band of 11 MHz. Further studies are planned to investigate the noise level coming from the new services, i.e. there is no final statement concerning how much spectrum will be available for PMSE systems. First measurements can be performed after first prototypes for LTE equipment are available for testing (late 2010 - early 2011).

5.1.5 863 MHz to 865 MHz

This band is an EC class 1 harmonised band for audio applications.

5.1.6 L-Band

5.1.6.1 L-Band part 1: 1 452 MHz to 1 477 MHz (1 479,5 MHz)

This frequency band is still under discussion in CEPT but may be added to CEPT/ERC Recommendation 70-03 [i.7] in the near future, i.e. this frequency spectrum may be available to PMSE in the near future. Potential usage in the UK is uncertain, as this frequency band was auctioned to a third party.

PMSE is secondary user; the primary user in this frequency band is broadcast distribution service T-DAB, etc. In the UK: Mediaflow.

5.1.6.2 L-Band part 2: 1 492 MHz to 1 518 MHz

This frequency band was studied. ECC Report 121 shows that it is a potential band, assigned to defence systems.

5.1.6.3 L-Band part 3: 1 518 MHz to 1 559 MHz

This frequency band has been studied by CEPT/ECC-SE24 as potential band for PMSE usage. CEPT/ECC-SE24 has conducted compatibility studies with primary services MSS and AMS(R)S. ECC Report 147 [i.11] may soon be finalized.

AMS(R)S working in the frequency bands 1 545 MHz to 1 555 MHz has a very high security status (ITU Radio Regulations) and is planned to be used in the future more extensively for airplane black box data transmission.

PMSE is a secondary user in this band; the primary service is MSS, AMS(R)S.

5.1.7 1,8 GHz: 1 785 MHz to 1 800 MHz

This frequency band is available for PMSE usage. It seems that manufacturers are planning to bring a product to the market next year. This band is a duplex guard band of mobile phone service, i.e. noise level has to be observed. PMSE is in most countries exclusively assigned to this frequency band.

5.1.8 ISM-band: 2,4 GHz and 5,8 GHz

Both bands are currently used by a wide range of SRD's, mainly radio LAN's. Audio use is mainly for conference systems. However due to the density of usage, ISM frequency bands will not be able to provide the requested QoS. PMSE manufacturer intend to search for alternative frequency bands.

5.2 Technical characteristics of specific frequency bands

Knowledge of the technical characteristics of the specific frequency bands is essential for developing cognitive functionalities. Therefore a propagation model has to be developed showing the appropriate frequency dependent values. This includes body absorption, wall absorption, fading, noise floor, etc.

6. Cognitive Technologies

This clause gives a definition of cognitive radio and provides a survey on the multiple technologies referenced under that term.

This clause focuses on the differences between cognitive radio technologies and traditional adaptive technologies when the goal is to protect PMSE systems from interference.

The clause provides the arguments to understand that traditional adaptive interference mitigation approaches are not sufficient to protect PMSE systems and justifies the use of cognitive approaches.

ETSI RRS has a project which is looking into cognitive radio technology with more general view, please see also TR 102 802 [i.13].

6.1 Definition of Cognitive Communication System

Cognition is related to the intelligent use of knowledge; it can be defined as the process of understanding the context in which a certain entity (person, network, radio device, protocol, etc.) finds itself and the reasoned judgment of the acquired understanding towards some goal.

For a wireless communication device, **context** involves:

- characteristics of the physical (e.g. location, indoor/outdoor) and radio-frequency (noise level, SNR, channel used, etc.) operational environment.
- user requirements (Quality of Service QoS or Service Level Agreement SLA) such as duty cycle, minimum SNR, BER, delay, channel bandwidth, channel spacing, etc.
- regulatory policies: EIRP, out-of-band emissions, etc.
- device capabilities: available modulation and coding schemes, frequency agility, receiver sensitivity, and range of transmit powers, etc.

Thus, a **cognitive communication system** (radio device, network, process) can be defined as an entity that is fully aware of the context in which it operates and autonomously arranges its processes according to that knowledge towards some goals. This definition assumes an underlying highly reconfigurable hardware/software platform and involves a decision-making process that matches actions or reconfiguration steps with requirements, constraints and possible conflicts. By feeding the decision-making process with knowledge about the grade of success or disappointment achieved by past actions, it is possible to enable the entity to learn from reoccurring situations and past experiences and thus, to recognize patterns of behaviour, evaluate risks and to use mechanisms for anticipating future events (prediction).

Figure 2 captures the functionality of a cognitive entity in the form of a cyclical process made of four stages: "observe", "understand", "decide" and "act". The stages "observe", "decide" and "act", can be seen as representative of any adaptive communication process such as link adaptation in HSDPA or WiMAX networks, or dynamic frequency selection in WLAN networks. The stage "understand" builds the breakthrough character of a cognitive entity and enriches the decision-making process with reasoning and learning achieved by the repeated running of the cycle (n cycles).

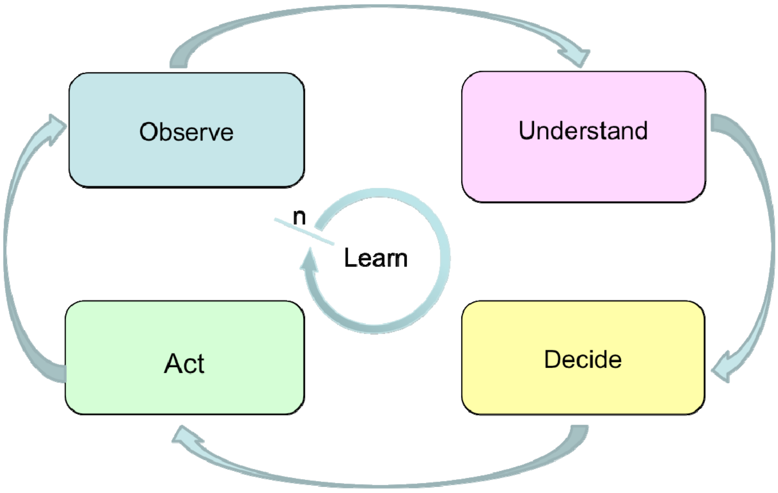

Figure 2: The cognitive cycle

Precisely, learning is what makes cognitive systems fundamentally different from current adaptive radios that perform predictable adaptations triggered by well-understood changes in the operation conditions (for instance adaptive modulation and coding). In contrast, cognitive systems are able to reconfigure themselves in unplanned ways as the result of the learning and reasoning processes. This breakthrough functionality comes certainly at the cost of complexity and needs to be justified in terms of efficiency. Figure 3 shows the relation between efficiency and complexity for current reactive adaptive systems and how this relation should be for cognitive systems in order to justify their development.

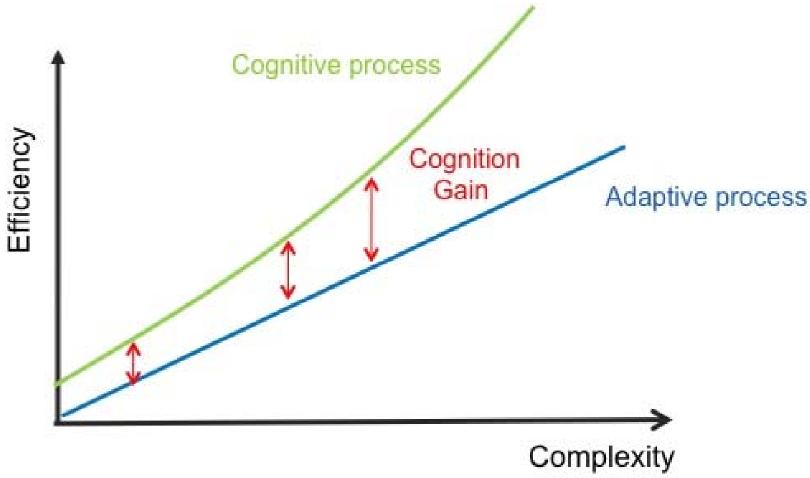

Figure 3: Complexity-Efficiency curve for reactive adaptive and cognitive systems

In a wider sense, one can say that understanding and learning are phases of the decision-making process. So, it is possible to include the processes 'understand' and 'learn' into the 'decide' block and obtain a simplified representation of the cognitive cycle. This is depicted in figure 4.

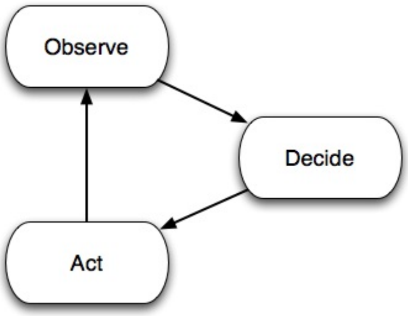

Figure 4: The simplified cognitive cycle

For the protection of PMSE, particularly for high quality audio systems, 'prediction' plays a key role since interruptions of the service quality are not tolerable. Therefore, cognitive PMSE systems are proactive, i.e. foresee link degradations and react to them adequately so that they can be avoided before they happen. This requires the extension of the usual cognitive cycle represented in figure 1 with a new functional stage, namely 'predict'.

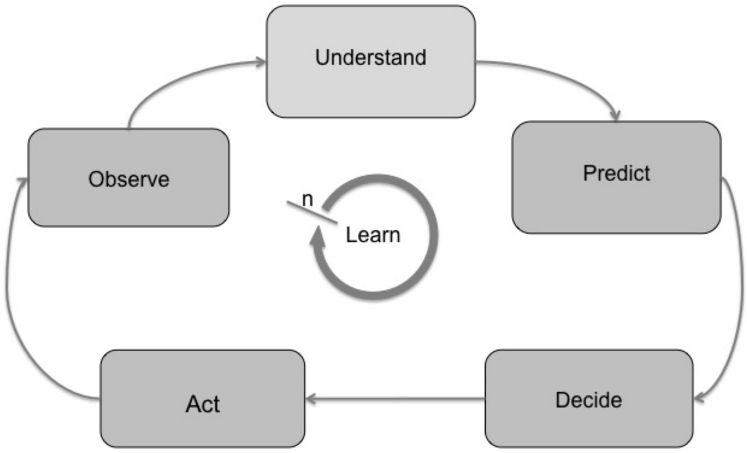

Figure 5: Cognitive cycle with predict

6.2 Functional Architecture of a Cognitive Radio

Figure 6 illustrates the architecture of a cognitive radio system and the interaction between its functional blocks.

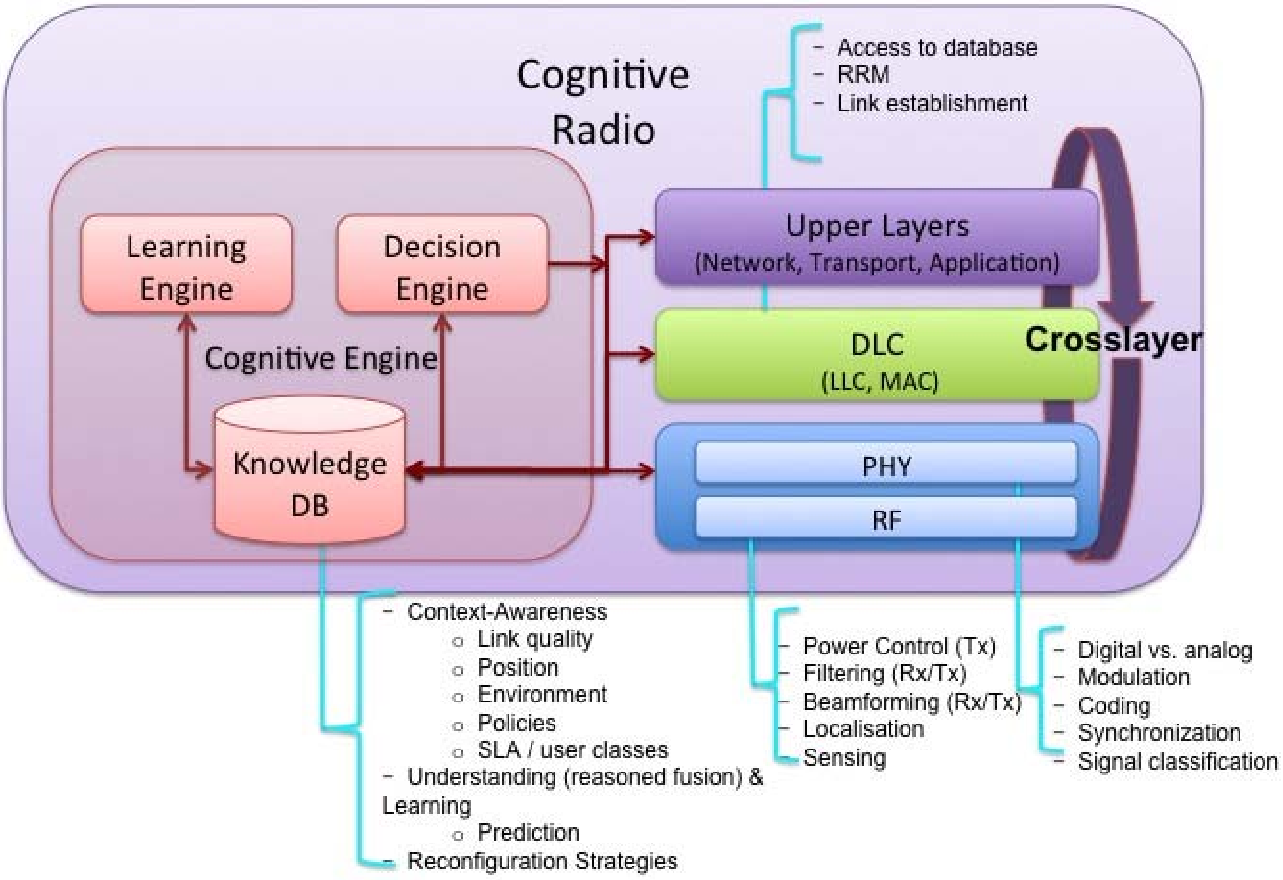

Figure 6: Cognitive Architecture

6.3 Cognitive Technologies

Based on the simplified cognitive cycle in figure 4, technologies related to cognitive communication systems can be classified into three categories:

- Technologies that enable the accurate observation of the operational environment. It is worth mentioning that the operational environment involves the radio and the geographical environments as well as the internal states of the cognitive radio system, for instance, spectrum sensing, geo-location, access to databases, or broadcasting and downloading information from a shared control channel.
- Technologies that underlay the intelligent decision-making and learning processes, for instance neural networks, genetic algorithms, Markov decision theory, game theory, statistical learning, etc.
- Technologies related to the actions a cognitive radio system can perform to configure its operation (parameters, behaviour), for instance dynamic frequency allocation, transmit power control, link adaptation, priority management, etc. These technologies are traditionally referred to as radio resource management (RRM) technologies.

6.3.1 Technologies for making observations

Observations may be done locally by the cognitive radio, but they may also be obtained as a download service from other entities such as databases or common organization channels (Cognitive Pilot Channel). Besides, observations may as well be shared between several cognitive radios in a cooperative way.

In general, the observation of the operation environment involves the gathering of the quality indicators stated in the service level agreement (SLA), the spectrum usage and the relevant regulatory policies. An external authority would usually deliver the latter.

6.3.1.1 Spectrum Sensing and Classification

Spectrum sensing, sometimes referred to as "detection", "sniffing", or "Listen Before Talk" in connection with Cognitive Radio systems refers to the technique of sampling a given frequency or band of frequencies to determine whether it is occupied by another user. Spectrum sensing is generally a passive process, and it should not interfere with other users of the spectrum. Although the term "spectrum sensing" is sometimes used interchangeably for "cognitive radio", the two terms have different meanings. As discussed above, a cognitive radio may incorporate spectrum sensing as well as other technologies to make decisions about how it should operate.

Characterising and cataloguing the sensed signals leads to classification. The related signal classification is typically based on signal analysis, which itself is based on detection processes and signal parameter estimations.

6.3.1.1.1 Energy Detection

Energy detection is a well-established technique for spectrum sensing. It has been widely applied in spectrum analyzers and many kinds of radio receivers, including wireless microphone receivers. Several variations are of interest. The sensing receiver can either be "fixed tuned" to a single frequency of interest, or it can be adjusted to "scan" across a band of frequencies to look for energy above a certain threshold. If it is necessary to scan multiple frequencies, then factors such as the tuning rate of the local oscillator and the settling time of the IF filters come into consideration. The output of the detector can be measured in a variety of ways and compared to a reference level or displayed visually; for example, in a spectrum analyzer. Matched filter detection is a subset of energy detection. Usually, the IF or channel bandwidth of the sensor will be chosen to be consistent with the intended type of transmission.

Many current PMSE receivers have the ability to scan a range of frequencies or a particular frequency of interest, but only at the start of operation. Once the PMSE transmitter has been switched on, that channel will be occupied with a 100 % duty cycle and scanning (on that frequency) is no longer useful (i.e. there are no "quiet periods" that can be used for sensing). From that point on, channel quality assessment becomes the main tool for determining whether operation is satisfactory, or whether the system should be switched to a new frequency. Currently, frequency switching is a manual process that requires operator intervention.

If it is necessary to detect very weak signals, e.g. below the noise level, repetitive scanning and signal processing techniques can be used. Some of the factors to be considered include the following:

- repetitive scanning and signal processing requires additional time, which is considered in the design of the system;
- the reliability of the detection process can be affected by the nature of the signal that is being targeted. For example, an analogue FM wireless microphone has a continuously variable spectral "signature". If there is no modulation (i.e. when there is no audio input to the transmitter), the emission will collapse to the carrier frequency only; possibly with low level sidebands present if tone control signals are in use. Control tones for PMSE systems have not been standardized but are typically in the 20 kHz to 40 kHz range and will generate sidebands at multiples of the control tone frequency;
- the reliability of the detection process can also be affected by energy spillover from adjacent channels. A certain amount of sideband energy is always present when a neighbour channel is in use, e.g. by a digital television signal;
- random noise bursts that occur during a scan can also be a problem. A single, low intensity noise burst may not be enough to disqualify the use of the channel, but if multiple high intensity bursts are detected, the channel should be avoided.

The main issue with energy detection is that it can take a long time if many frequencies are to be scanned, or if weak signals are to be detected.

6.3.1.1.2 Feature Detection

The main premise behind cyclostationary feature detection is that the spectral signature of the signal to be detected is known in advance. A "snapshot" of appropriate spectral bandwidth is typically flash converted to baseband and compared to the known (or expected) signature(s) for identification. This technique can work very well for detecting and identifying emissions that have unique and relatively constant features. It can also be used to successfully detect signals that are at or below the noise floor through the use of correlation techniques. However, it has limitations too:

- selective fading due to multipath can corrupt the spectral signature of the received signal and make identification difficult or impossible.
- for obvious reasons, the characteristics or "features" of the target signal is known in advance in order to identify it. However, if this is not the case, the signal can still be characterized, and its profile could be stored for later analysis and classification.

6.3.1.1.3 Limitations and Challenges

Currently, there are number of problems with the use of spectrum sensing to protect PMSE systems from interference. The issues are shown through the example of TV band devices (TVBD) that are expected to enter the TV spectrum in the USA shortly. These problems generally fall into one of the following categories:

- false negative detection: The sensing receiver in the TVBD fails to detect the PMSE transmitter (e.g. a wireless microphone) and concludes that the frequency is unused and therefore available. When the TVBD transmitter begins operation, interference to the PMSE system is likely. False negative detection is measured in terms of probability of misdetection (P_{md}).
- false positive detection: The sensing receiver in the TVBD determines that the frequency is occupied when it actually is not. This will not cause interference to the PMSE system, but results in spectral inefficiencies and may cause the user of the TVBD to conclude that it is not working properly. This in turn may lead to attempts to defeat the spectrum sensing system and force the TVBD to transmit on a channel that is in use by PMSE, causing interference. False positive detection is characterized in terms of probability of false alarm (P_{fa}).

Thus, we conclude that both false negative and false positive detections are problematic. Let us consider the underlying causes for each outcome.

False negatives occur when the PMSE transmitter signal is too weak at the location of the TV band device to be detected. Unlike mobile phones and similar devices, for a PMSE system, the transmitter and receiver are in different locations. The TVBD sensor can only detect the PMSE transmitter, but it is the PMSE receiver that is vulnerable to interference. The sensor in the TV band device may not detect the PMSE transmitter (Mic1), either because it is blocked by local obstructions or in a "null" caused by multipath interference. When the TVBD transmitter (device 1) begins to operate, it can cause interference at the PMSE receiver's location (Rx1). This is sometimes referred to as the "hidden node" problem (figure 7). The use of "cooperative sensing" can help reduce the probability of occurrence. With cooperative sensing, each sensor operates independently and shares its detection results with the other devices in its network as shown in figure 8.

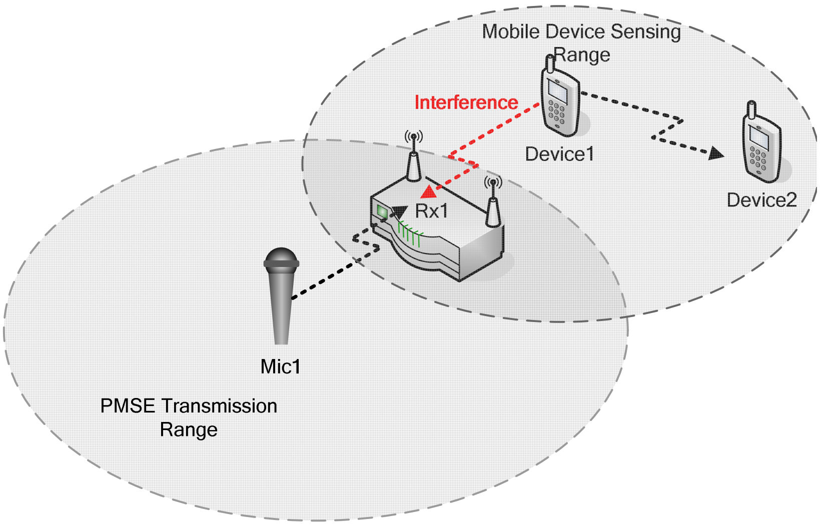

Figure 7: Hidden node problem

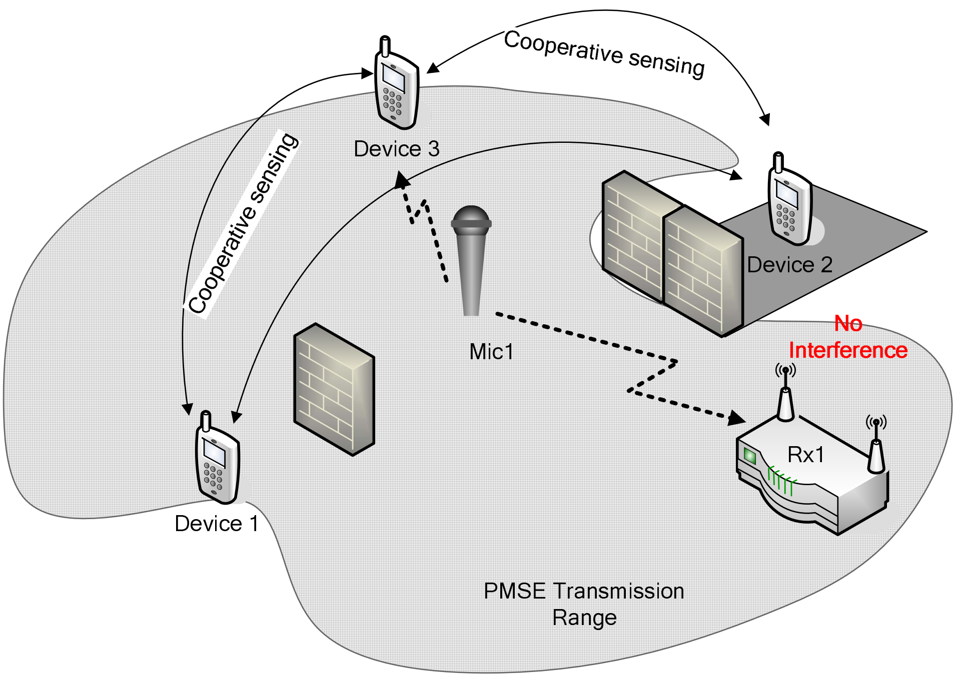

Figure 8: Cooperative Sensing

Detection failures can also be caused by other factors:

- there may be a disparity between the power of the PMSE transmitter and the TV band device transmitter. For example, if the PMSE transmitter only transmits at 10 mW EIRP and the TV band device transmits at 500 mW, there is a risk that the interference range of the TVBD transmitter will exceed the sensitivity of its sensing receiver.

- the TVBD sensor may be overloaded by out-of-channel or out-of-band signals, causing its sensitivity to be degraded and leading to false negatives. This occurred during tests at the U.S. FCC laboratory [i.12]. TVBD sensors are designed to meet required sensitivity specifications in the presence of relatively strong out-of-band signals. For example, during its field tests, the FCC measured DTV signals at -20 dBm in adjacent channels.

- the TVBD sensor may be "fooled" by energy spillover from adjacent channels, leading to false positives. For example, if there is a strong television signal on an adjacent channel, it is likely that a significant amount of sideband energy will be present. This is exacerbated by the fact that the sensor usually detects very weak signals (e.g. in the range of -114 dBm to -120 dBm).

In order to preserve the SLA expected by PMSE users, spectrum sensing performance would need to reach the point where false negative responses are under 1 %. As previously discussed, false positives should also be minimized as much as possible. The performance of present-day sensors falls far short of these levels. Proponents have argued that the sensing thresholds need to be relaxed in order to improve sensing performance, but this is not a viable solution for protecting low powered PMSE systems.

In summary, the following aspects of spectrum sensing need to be improved in order for this technology to be a viable means of protecting PMSE systems from interference:

- both false negative and false positive detection rates need to be reduced significantly.

- the sensor is able to detect PMSE transmitters at a fairly low level and this level is maintained in the presence of strong adjacent channel and out-of-band signals.

- scanning times is reduced to the point where they are not an impediment to the TVBD user.

It is apparent that much work remains to be done to perfect this technology. Meanwhile, spectrum sensing remains useful as an assessment tool for determining whether a given frequency or group of frequencies is viable for PMSE use. Due to the fact that PMSE transmitters operate with a 100 % duty cycle with no quiet periods, this assessment can normally only be done before PMSE transmitters are powered on. However, it might be possible to extend its use to sensing during system operation to determine other frequencies that could be used if a given frequency were to become unusable during an event.

6.3.1.2 Radio Environment Map

Radio environment map (REM) is a general term used in the cognitive radio literature to refer to a knowledge database where multi-domain information relevant to a cognitive communication system, for instance information about spectrum regulation or location-based and real-time spectrum usage, is stored.

The REM can be seen as a vehicle for management support and information sharing between dissimilar cognitive systems (inter-system) or between entities of the same cognitive system (intra-system).

The benefit of using REM is that not every cognitive system needs to perform spectrum sensing to acquire context-awareness as long as it has access to an up-to-date REM. Furthermore, the REM can be exploited by the cognitive systems for other cognitive functionalities such as reasoning, learning and decision-making.

By sharing information about the operational environment (geographical and radio), global optimization of the cognitive systems can be leveraged. For instance, it can help reducing the hidden node problem improving coexistence among primary and secondary systems.

The critical points of this technology are:

- the access to the database;

- information availability.

Regarding the access to the database, web-based database (i.e. the database is built as an internet accessible server) technology will allow cognitive radios to access the REM in either centralized or distributed ways. Regarding the access interface, we can distinguish among machine-to-machine interfaces (MMI), i.e. the cognitive radios access the database directly without human intervention, and human-to-machine interfaces (HMI), i.e. the user of the cognitive radio accesses the database through a graphical user interface (GUI). For the latter case, user-friendly visualization tools are required.

EXAMPLES:

- JFMG.co.uk in the UK.
- SpectrumMap [i.2] is a prototype system that aims at visualizing location-based or time-based information of spectrum resources. It combines spectrum analyzer, geolocation based on Global Positioning System (GPS) and the Microsoft Virtual Earth platform.
- WiMaX forum spectrum and regulatory database [i.3].

Once the access to the database is technologically possible, many questions arise:

- Who can/should update the information in the database?
- How often?
- How accurate is the information that enters the database?, etc.

Regulatory authorities will have to enter regulations, recommendations and policies in an on-event basis. Cognitive radios with spectrum sensing capabilities can enter their observations in the database on a periodical basis, sharing in this way their own environmental view with other cognitive radios.

The accuracy and precision of the information entered in the database will determine the success of the optimization approaches. Clause 6.3.1.1.3 deals with the problems related to spectrum sensing and clause 6.3.1.3 deals with the accuracy and precision by the acquisition of geographical (position) information.

6.3.1.3 Localization

Regarding context-awareness, the location at which a radio device operates is a very important piece of information since the effects of radio propagation and spectrum usage depend strongly on it. This clause describes the state of the art of positioning technology and the implications for the success of the REM concept to protect PMSE devices.

Providing high location accuracy, the global frequency allocation table becomes a local one with its granularity depending on the location accuracy. The allocation table expands to a precise REM depicting all local useable frequency resources, which leads to higher spectral efficiency.

Regarding the acquisition of location information, there is a relative confusion in the current literature between the terms "localization", "positioning" and "ranging". Thus, it is worth beginning this clause by clarifying these terms.

Both 'positioning' and 'localization' indicate the action of computing the position of a target object with respect to a reference object from which the position is known. In the context of wireless networks, the target objects are nodes of the network.

Ranging consists of computing the distance of a target object (node) from a reference object (node). The reference node establishes a bidirectional communication link with the target node and evaluates some characteristic of the channel; typically the received signal strength and / or propagation delay. With multilateration of several ranges it is possible to determine the position of a radio device.

Positioning techniques can be classified in two groups:

- infrastructure-based (absolute positioning): GPS for outdoor; Wi-Fi, RFID and UWB for indoor;
- non-infrastructure based, i.e. ad-hoc positioning (relative positioning), which is possible if both angle and range information are available.

6.3.1.3.1 Expected performance of indoor geolocation technologies

Mobile systems provide geolocation accuracy in the range of a few hundred of meters. This is insufficient for PMSE systems.

Wi-Fi systems working in the infrastructure mode provide geolocation accuracy in the range of a few meters.

Geolocation is based on the evaluation of the received signal strength (RSS) from several access points at the target. The main drawback of this method is that the offline phase is repeated every time something changes in the environment (movement of an object, target antenna, etc.); an offline phase is necessary. In this offline phase the area is divided in a grid and at each point of the grid the target measures the RSS from each AP and stores it in a database. During the geolocation procedure, the target compares the current RSS measurements with the data stored in the database and chooses the location (point of the grid) with the most similar RSS values.

Geolocation based on RFID requires the deployment of a grid of RFID passive devices on the floor of the area. Each RFID passive device has a unique position associated with it. When the target moves over a RFID device, it can detect the presence of the target and determine its coordinates (those of the RFID tag). The accuracy depends on the granularity of the grid. The limitation is given by the detection range of the RFID devices, which accounts to 1 meter to 1,5 meters.

UWB is the geolocation technology that provides the best performance in indoor environments. The high temporal resolution of UWB signals can lead to accuracy in the range of a few centimeters.

6.3.1.4 Cognitive Pilot Channel

The Cognitive Pilot Channel (CPC) [i.1] is a channel that carries information about the available operators, Radio Access Technologies (RAT) and used frequencies in a given area, so that a mobile terminal is able to quickly obtain information about the spectrum usage. Otherwise, the mobile terminal has to sense the spectrum and detect the spectrum usage, which might take a long time and is also power consuming.

6.3.1.4.1 Information transmitted in the CPC

The data transmitted in the CPC is operator based. Every operator offers a number of RATs, and the RATs work in (a) specified frequency range(s).

The mobile terminal is only interested in the information relevant to his current location.

The more operators that are active in a given area, the greater the amount of information that has to be transferred in the CPC, so that the access time for a mobile terminal to extract the information that is relevant to him increases. The access time can be reduced if a wideband channel with high data rate is used for the CPC.

6.3.1.4.2 Operation modes

There are three possible operation modes:

- **Out-band CPC:** a new, universal frequency and different from the existing RATs carries the CPC.
- **In-band CPC:** this approach uses channels from existing access technologies for transmitting the CPC.
- **Combined CPC:** this is a combination of the out- and in-band approaches. In the out-band CPC, a minimum of information of operators and RATs is transmitted. With this information, a mobile terminal is able to quickly find the in-band CPC and get additional information. With this approach, the terminals do not have to scan the whole spectrum, but a worldwide harmonized frequency is also necessary.

6.3.1.4.3 Delivery modes

There are two possible delivery modes:

- **Broadcast:** This mode uses a downlink CPC, where all the information about the area is continuously and periodically broadcasted. The terminal detects the CPC and simply has to wait until the information according to his location is transmitted. The total access time for a terminal depends on the data rate of the CPC and the number of operators/RATs that are transferred.
- **On-demand:** The broadcast approach might either require a long time or wideband channel. As a result, it might become more power and bandwidth efficient if the information is only transmitted on demand. The on-demand access can follow a scheme similar to the channel request procedure in mobile systems.

6.3.1.4.4 Benefits of CPC

CPC could provide global support for mobile terminal reconfigurability and best use of available resources by disseminating context-related information such as accessible operators and RATs and current resource usage.

6.3.1.4.5 Drawbacks of CPC

Some drawbacks of the CPC are:

- **spectrum inefficiency:** additional channels are required so that either new channels have to be established and harmonized or existing channels have to be modified in their use.
- **scalability:** the more information is transmitted on the CPC, the more the context-awareness of the mobile terminals can be enriched, but at the same time the more resources (channels, bandwidth) are consumed and the longer a given mobile terminal may need to wait to access the information that is relevant to him.
- **centralized character:** if the CPC conveys false information (simply out of date or even with malicious intentions), all mobile terminals in the coverage area can be influenced to behave improperly, leading to catastrophic situations.

6.3.2 Technologies for making Actions: Radio Resource Management (RRM)

In order to make use of cognitive radio resource management technologies, a control channel (e.g. downlink from master to slaves) is necessary.

Today most PMSE systems use analogue transmission. Analogue technology is very mature and provides a high Quality of Service, but in the future, PMSE systems can be expected to increasingly adopt the use of digital transmission. Radio Resource Management technologies can be applied to both analogue and digital PMSE systems, but certain techniques are only applicable to digital systems. Table 3 gives a general indication of which RRM technologies could be applied to analogue and digital PMSE systems.

Table 3: RRM

RRM Technology	Applicable to Analogue Systems	Applicable to Digital Systems
Dynamic Frequency Allocation (DFA)	Yes	Yes
Bandwidth Scaling	No	Yes
Dynamic Power Control (DPC)	Yes	Yes
Pre-emption / Priority Management	Yes	Yes

These RRM technologies are discussed further in the clauses 6.3.2.1 to 6.3.2.4.

6.3.2.1 Dynamic Frequency Allocation (DFA)

Dynamic Frequency Allocation (DFA) involves the process of selecting a frequency that is unoccupied and free of interference for a radio system to operate on. It is generally regarded as one of the most important components of a Cognitive Radio system. Frequency allocation is normally performed at system start-up but could also occur during operation if the current operating frequency becomes unavailable. Input to the frequency allocation process could be derived from a spectrum sensing algorithm or from a database (or both).

Current PMSE systems do not employ Dynamic Frequency Allocation. The frequency plan is developed in advance of an event, and is typically not changed unless there is a problem. A well-designed plan will include extra frequencies that could be used if necessary. However, frequency adjustment typically requires user intervention and therefore can be problematic if required during an event.

The main benefit of adding DFA to PMSE systems would be to enable the system to adapt to changes in the radio environment, e.g. the appearance of an unexpected interfering signal. To implement Dynamic Frequency Allocation in PMSE systems, a control channel from the infrastructure node to the mobile node is required. The big issue that needs further work is to determine whether the required quality of service can be maintained during a frequency change operation. Outages, including noise bursts such as "clicks" or "pops", are not tolerated. Aside from these limitations, DFA could be applied to either analogue or digital PMSE systems.

6.3.2.2 Bandwidth Scalability

The main purpose of bandwidth scaling is to adjust the amount of spectrum occupied by a radio system in accordance with its quality requirements. A narrower band will typically support a lower data rate, resulting in lower quality transmission in terms of audio bandwidth and/or Signal-to-Noise Ratio (SNR). A secondary effect (and potential benefit) of using a narrower bandwidth is an improvement in link margin, assuming that the receiver filter bandwidth is reduced accordingly. Present-day PMSE systems do not implement bandwidth scaling, and it is not applicable to current analogue systems.

There are potential benefits from the use of bandwidth scaling in PMSE systems. The most obvious one is that it might be possible to deploy more wireless links in a given amount of spectrum if each one takes less bandwidth. Unfortunately there is not a 1:1 relationship between occupied bandwidth and spectrum efficiency, since Intermodulation Distortion (IMD) products also have to be considered.

6.3.2.3 Dynamic Power Control (DPC)

Dynamic Power Control (DPC) enables the transmitter power to be adjusted dynamically in accordance with link requirements. It is applicable to both analogue and digital systems. Ideally, the transmitter should be operated at the minimum power required to maintain the link with an acceptable SLA. Some important parameters for DPC include the power step size and accuracy, power control range, and update rate. A critical problem is the control loop, which should not blindly increase output power without analysing the REM and the possible increase of interference, which might hurt neighbour systems.

Another limitation of DPC is the increase of the number of hidden nodes, since the detection range of the PMSE transmitter is reduced with reduction of RF output power.

6.3.2.4 Pre-emption - Priority Management

One of the challenges for PMSE in the future is the increasing demand for wireless audio channels. At the same time, the amount of spectrum available is likely to continue to shrink. Cognitive Radio techniques can help this situation, but will probably not be sufficient to provide a complete solution in the near term at least. Therefore, some consideration should be given to priority management and pre-emption. This includes provisions in the Radio Resource Management scheme to allow lower priority wireless links to be added or dropped or to have their SLA adjusted in accordance with available resources (i.e. adequate spectrum). This would allow the PMSE producer to designate priority levels in accordance with production requirements. This means that they might be provided with a lower quality channel in terms of link reliability or audio quality.

7 Cognitive PMSE System (C-PMSE System)

This clause builds on the previous clause and for clarity we have used the used the term cognitive PSME system (C-PSME) when describing cognitive requirements for PMSE.

7.1 Definition C-PMSE

Relying on the ETSI definition [i.4] for a cognitive radio system, a cognitive PMSE system (C-PMSE) is defined as a PMSE system (it may include multiple radio links and network elements) capable of:

- obtaining knowledge from the operation environment in which it finds itself;
- dynamically, autonomously and whenever possible proactively adjusting its operational parameters and protocols according to this knowledge in order to achieve predefined objectives, e.g. avoid service level agreement violation, minimize the effect of performance loss or increase spectral efficiency;
- and learning from the results of its actions in order to further improve its performance.

The functionality behind this definition can be abstracted as the cyclic interaction of five processes, namely ''observe', 'understand', 'predict', 'decide' and 'act', as shown in figure 9.

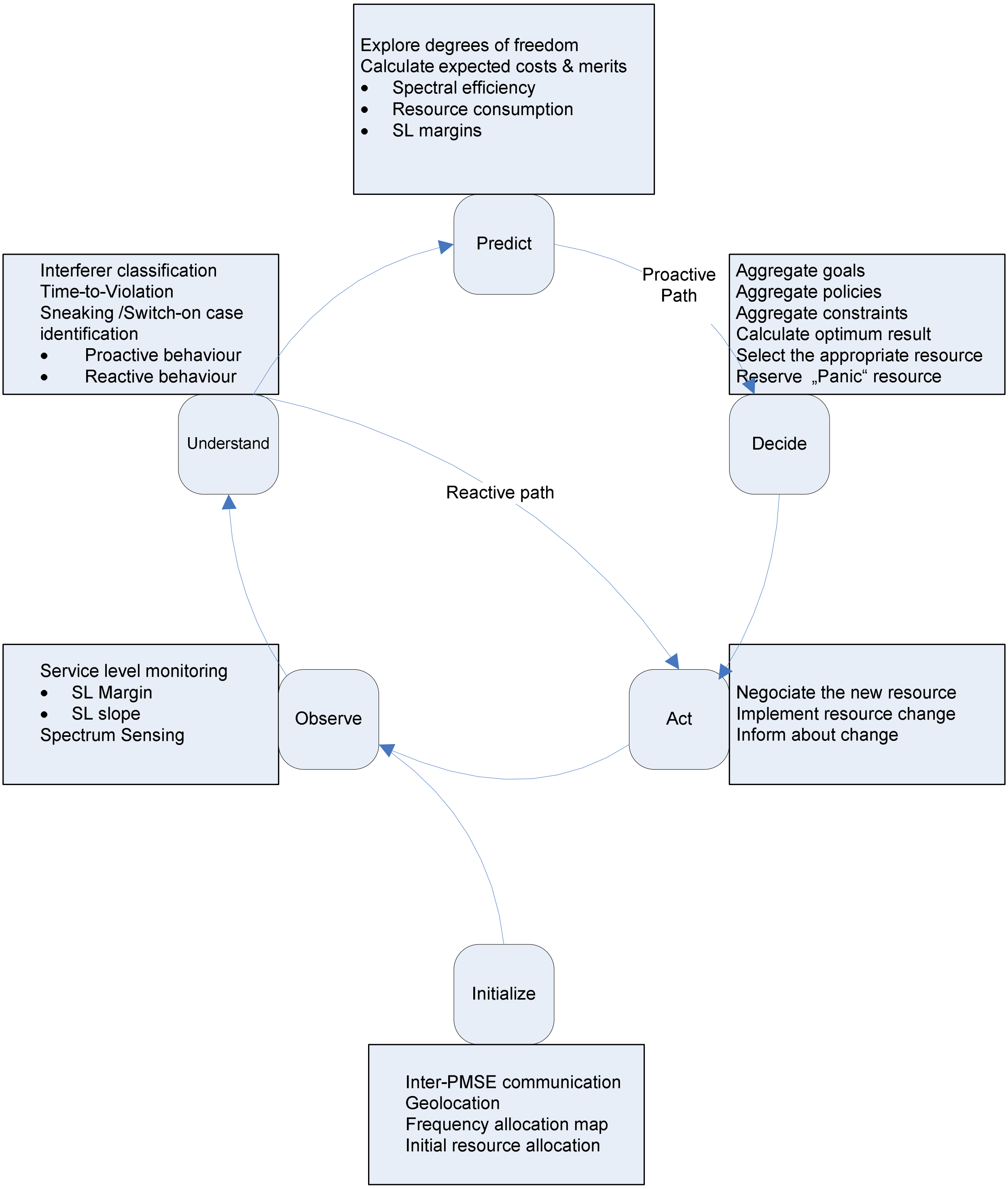

Figure 9: Cognitive cycle, functionality

The following clauses provide further information on these processes.

7.1.1 Observe

This functional block refers to the gathering of the operational environment, which includes the radio environment as well as the internal states of the C-PMSE system. Observations may be done locally by the C-PMSE system, but they may also be obtained as a download service from other entities such as databases (Frequency Coordinator) or common organization channels (Cognitive Pilot Channel). Observations may as well be shared between several C-PMSE systems in a cooperative way. This collaboration requires the definition of an inter C-PMSE interface (see cpi). The observation of the radio environment involves the observation of the spectral usage and of the legal issues and policies at the location of the C-PMSE system.

Regulations and policies are usually provided by external authorities.

The observation of the spectral usage can be supported by the use of scanner-receivers or by the use of REM.

The observation of the internal state of the C-PMSE system implies the monitoring of multiple signal quality indicators stated in the SLA.

7.1.2 Understand

This functional block refers to the transformation of the observations into knowledge. This transformation may involve the generation of new insights, the recognition and possible classification of patterns of behaviour and risks.

It also allows extracting knowledge about the grade of success or disappointment achieved by past actions. In this way it is possible to enable the C-PMSE to learn from reoccurring situations and the past.

The acquired knowledge may include:

- interferer classification;
- service level violation.

If the service level agreement is violated, i.e. it is below the agreed quality threshold, then the C-PMSE understands that a critical situation is going to occur and that there will be no time to follow the proactive path of the cognitive cycle. It then shortcuts the cycle and goes directly to the 'Act' functional block. In this case, the C-PMSE can be seen as a fast reactive system, which has a set of predefined actions for critical situations (called 'panic resources'). There should exist a set of 'panic actions' known upon system initialization, but this may change over time through learning.

Otherwise, the proactive path of the cognitive cycle can be followed.

7.1.3 Predict

This functional block is the key enabler for the proactive character of the C-PMSE.

It is in charge of evaluating:

- The risks that threaten the accomplishment of the SLA; for instance, the Cognitive Engine (CEN) can compute the expected "Time to Violation" (TTV), that is the expected time after that a violation of the SLA may occur.
- The degrees of freedom of the C-PMSE, i.e. which are the expected costs and merits related to the actions that the C-PMSE could take in the current context / environment.

The output of the 'predict' process enriches the decision process with information about the expected occurrence of conflicts and the consequences of the decisions that the C-PMSE could take for protection.

7.1.4 Decide

The decision process consists of finding the configuration parameters that best fit the goals of the C-PMSE given the set of applicable constraints and policies.

The core of the 'decide' functional block is a multi-objective cost/utility function capturing:

- the goals of the C-PMSE system, e.g. maximize spectral efficiency, SLA fulfilment, etc.;
- the constraints imposed by regulation or hardware capabilities:
  - spectral mask;
  - ranges and granularity of adaptations;
- the applicable policies:
  - Ask Before Talk (ABT), Listen Before Talk (LBT), etc.

The decision-making process implies the optimization of the multi-objective cost/utility function.

7.1.5 Act

This functional block closes the cycle by implementing the decisions taken in the 'decide' step.

The actions imply the reconfiguration of the radio resource management parameters of the C-PMSE system.

7.2 C-PMSE System Architecture

The architecture of the signalling plane of a cognitive PMSE system is described in this clause. Its block diagram is shown in figure 10.

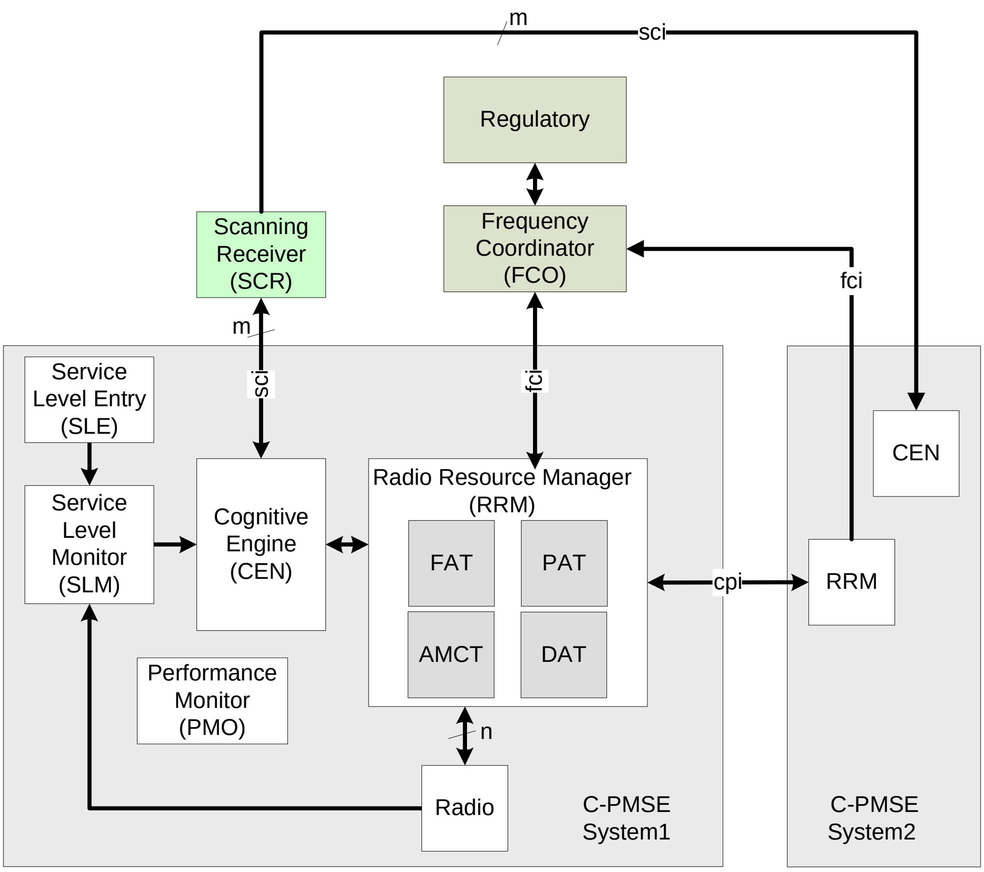

Figure 10: Block diagram of C-PMSE system

The architecture is composed of the following functional elements:

a) Radio Resource Manager (RRM) with:

   i) Frequency Allocation Table (FAT);

   ii) Power Allocation Table (PAT);

   iii) Adaptive Modulation + Coding Table (AMCT);

   iv) Device Allocation Table (DAT);

b) Service Level Entry (SLE);

c) Service Level Monitor (SLM);

d) Cognitive Engine (CEN);

e) Performance Monitor (PMO);

f) Up to n Radios.

The CEN gets all required information from the SLM and external frequency scanners to perform the cognitive process. The outcome of this process is used by the RRM to update the different allocation tables, which control the radios, and send it back to the frequency coordinator. A link quality indication is sent from every radio to the SLM, which compares actual measured values to a certain threshold and calculates operating margins set by the user via the service level entry. The RRMs of different C-PMSE systems are capable to share and exchange system information between each other.

Three bidirectional interfaces, which have to be standardized, are depicted in figure 10:

a) cpi interface for inter C-PMSE communication;

b) fci interface for communication between C-PMSE and a frequency coordinator;

c) sci interface for communication between external scanning receivers and the cognitive engine of the C-PMSE.

7.3 Description of Functional Elements

7.3.1 Radio Resource Manager (RRM)

The RRM manages the radio resource parameters. One RRM also defines a cell or one C-PMSE. Furthermore the RRM hosts various tables:

- FAT - Frequency Allocation Table;
- PAT - Power Allocation Table;
- AMCT - Adaptive Modulation and Coding Table;
- DAT - Device Allocation Table.

The FAT is a small local database that hosts a list of frequencies that have been granted by the FCO (Frequency coordinator). Within that table also the frequencies actually in use by the various audio links are marked, together with their associated pre-emption level.

The PAT table lists the power assigned to each audio link respective the used frequencies. The AMCT hosts a lists of Adaptive Modulation and Coding parameters, e.g. what modulation format (analogue/digital) with which parameters e.g. FM deviation and what channel bandwidth is actually used. It may also contain source coding parameters such as what compander type or what audio compression scheme is applied.

The DAT is a database that hosts a list of devices installed. It contains information on what equipment is used for each audio link. In essence it tells which manufacturer's equipment is used for what audio link. For an uplink audio link, it contains the wireless microphone and receiver product code. The product code is important as specific interference robustness parameters such as the transmitter intermodulation and receiver linearity are associated with it. In the SLE certain pre-emption levels may also be set for each audio link. These pre-emption levels are also stored in the DAT.

Another information stored in the DAT is the number of scanning receivers SCRs, their capabilities and their location.

The various tables contain information about spectrum and more general radio resource occupation by a C-PMSE, which will also be passed to neighbour C-PMSEs via the inter C-PMSE interface (cpi).

All tables are dynamic due to the fact that a C-PMSE will conduct RRM changes automatically.

7.3.2 Service Level Entry (SLE)

The SLE is a Human Machine Interface (HMI) for manual feeding of the SLM. The user enters his specific value of service level parameters and the thresholds he needs for running his application. Every audio link gets its own individual set of service level parameters.

7.3.3 Service Level Monitor (SLM)

The SLM observes the quality of all active radio links within its C-PMSE on the basis of measured link quality parameters provided by the radios, e.g. BER or RSSI, or other interference measurement metric. It has two kinds of input data: user defined thresholds provided by the service level entry and real-time measurement results provided by each radio. The monitor itself compares the measurement results with given thresholds and calculates service level operating margins and their slopes.

The calculation result is fed into the cognitive engine to be used during its 'understand' and 'predict' phases.

7.3.4 Cognitive Engine (CEN)

CEN is the functional element that turns a classical PMSE into a C-PMSE (Cognitive PMSE system). It hosts the intelligence to optimize the system operation.

During the cognitive cycle several phases "observe", "understand", "predict", "decide", "act" are undergone. In order to perform each phase, the CEN has access to various other functional elements such as the Service Level Monitor (SLM), Scanning Receiver (SCR), and Radio Resource Manager (RRM).

Link Adaptation (LA), which means adjusting the radio parameters of a wireless link, also resides in the CEN in order to decide which parameters should be altered. However, the conduction of changes resides in the RRM and the affiliated radios.

It may be stated here that the system is cognitive, not a device such as a wireless microphone. The term "cognitive device" may not be appropriate in the context of PMSE systems.

The CEN has an extended characteristic over classical Cognitive Radios in the way that it is acting proactively and reactively. Proactive means that if the CEN observes that the margin to a certain guaranteed service level is continuously decaying e.g. by an interferer that is slowly approaching, it will take a precautionary action to alter RRM parameters as it can predict that soon the minimum guaranteed service level will be violated. This represents the proactive scheme implemented in the CEN. However, also the classical reactive scheme is implemented. This means that if a minimum service level is violated, it will take immediate action to change RRM parameters.

7.3.5 Performance Monitor (PMO)

The PMO provides dynamic insight into actual parameters of the RRM, CEN and SLM. It is a human-machine-interface allowing a human to inspect a C-PMSE system. Typically this will be realized as some sort of web interface.

PMO will allow looking into actual RRM settings, such as actual frequencies in use (FAT), actual transmission power settings (PAT) and actual settings with modulation (AMCT).

In order to gain insight on the processing of the cognitive engine (CEN), a report at every transition between phases of the CEN is provided to the PMO.

The PMO will also be very helpful in coordinating a C-PMSE with an old legacy PMSE. The human frequency coordinator of a legacy PMSE can look at the C-PMSE and see e.g. what frequencies and power levels were selected automatically by the CEN.

7.3.6 Scanning Receiver (SCR)

The SCR is a frequency scanning element which can be a fixed installed device, e.g. in an event hall, or an additional element of a mobile system. In both cases the SCR provides on demand the cognitive engine with data of the radio environment. The installed SCR's can be accessed by several C-PMSE. Depending on the request, the SCR is able to perform at least energy detection with a predefined measurement setup consisting of:

- resolution bandwidth;
- swap time;
- centre frequency;
- scanning range (number of points);
- kind of detector (rms or max peak or both).

For higher classification schemes inside the cognitive engine, it might be necessary to perform feature detection with a time domain snapshot of a longer time period and afterwards do post-processing calculations, e.g. FFT. The kind of data acquisitions and the complexity of the post-processing procedure condition the amount of data which have to be provided by the interface between SCR and the cognitive engine.

7.3.7 Frequency Coordinator (FCO)

The FCO is an important resource for the "Ask Before Talk" function of the Cognitive PMSE system. The FCO includes information from the spectrum regulator, neighbour C-PMSEs, and the local C-PMSE in a hierarchical order, as shown in figure 11.

primary service Assignment/Reservation (Regulator)
Neighbour C-PMSEs
Local C-PMSE

Figure 11: FCO

The highest level of the FCO serves as the interface to the regulatory regime in effect at the location of the C-PMSE. The interface may be directly with the regulator or with an agent that acts on behalf of the regulator such as a "band manager" or "database operator". At a minimum, the regulatory interface includes information which frequency ranges are legal for use. It may also include reservations made by the C-PMSE operator with the regulator's database for specific spectrum grants of channels or frequencies in accordance with applicable band plans, as well as lease times and location information. If the regulator maintains an online database, the Frequency Coordinator connects to the database or to additional databases as necessary.

The intermediate level of the frequency coordinator contains information about frequencies in use by neighbour C-PMSEs when they are present, as for example during a large event. The Frequency Coordinator grants specific frequency assignments to neighbour C-PMSEs upon request. This level may or may not be present depending on individual requirements.

The lowest level of the FCO contains information on specific frequencies used by the local C-PMSE system. This level is always present.

7.4 Interfaces/Protocols

This clause provides information about the CEN interfaces, which need to be standardized. It is listed which information needs to be transferred with its specific protocol.

7.4.1 Frequency Coordination Interface (fci)

fci is a bidirectional interface between RRM and FCO.

7.4.1.1 Information provided from FCO

Link parameter to use:

- List of frequencies, o.k. for use;
- Associated power level, RF bandwidth, etc.;
- Location with location accuracy;
- Lease time.

7.4.1.2 Information provided to the FCO

- Location:
  - with location accuracy;
  - indoor / outdoor;
  - other possible values: propagation characteristics of the location.
- Device type;
- RF specifications / preferences.

7.4.1.3 Other organizational aspects / open issues

- Credential and security: access rights.
- Speed of update; to and from the FCO.

7.4.2 Inter cognitive PMSE Interface (cpi)

cpi is the bidirectional interface between co-located C-PSMEs interchanging following information:

- Location with location accuracy;
- RRM tables:
  - Frequency Allocation Table (FAT);
  - Power Allocation Table (PAT);
  - Adaptive Modulation and Coding Table (AMCT);
  - Device Allocation Table (DAT).

7.4.3 Scanning Receiver Interface (sci)

The sci interface standard needs to offer the possibility of adaptation to different classes of scanning receivers, i.e. the protocol needs to be expandable.

Standard values (not defined yet) could be location with location accuracy, scanning results, etc. Additional, advanced features could be antenna line array, FFT calculations etc.

8 C-PMSE Scenarios and Use Cases

8.1 Introduction

A centralized system is described in the present document because every professional wireless microphone system (PWMS), independent of its size (its number of audio channels), every intercom and every conference system of today and with high probability of the future, fits into this centralized system approach. In applications where a nomadic node is existent, it is called infrastructure (e.g. the receiver of a wireless microphone). Such systems are composed of an infrastructure and a configurable number of mobiles (e.g. the wireless microphone), which have a point-to-point connectivity with the infrastructure but no inter-mobile connectivity. The infrastructure - mobile link has broadcast and/or point-to-point connectivity depending on its content / application. Other applications are composed of mobiles only (e.g. ENG) and provide inter-mobile communication only. In every application there is one dedicated master and an arbitrary number of slaves. Normally if an infrastructure is present, it will be the master of the system. For a system with mobiles, only one mobile has to be assigned to be its master. The slave - master link is called uplink, the master - slave link downlink, which is shown in figures 12 and 13 for three different applications: wireless microphone (figure 12), wireless IEM (figure 12), and wireless conference system (figure 13). Depending on the kind of application, there is unidirectional or bidirectional communication. The audio stream (content plane, see figures 12 and 13) can be transmitted in the uplink (wireless microphone), downlink (IEM), or in both uplink and downlink (intercom, conference system).

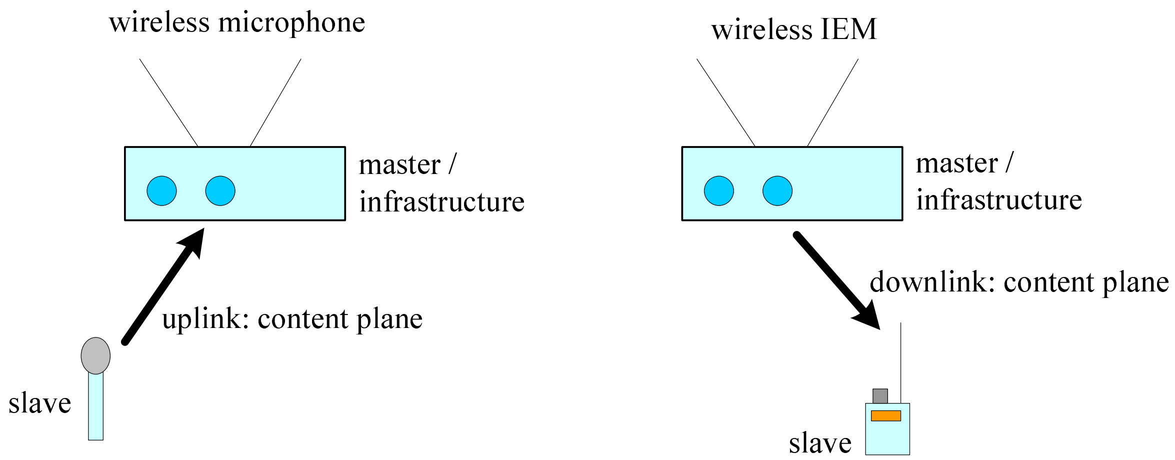

Figure 12: Terminology for wireless microphone and wireless IEM

In current PWMS and IEM, there is no additional RF link for system management purposes. For cognitive functionality, the infrastructure node needs a facility to organize and configure its own mobiles before and during operation. This leads to two different kinds of physical channels:

a) downlink: communication from master to slave;

b) uplink: communication from slave to master.

In addition there is a differentiation of the connectivity of the physical channels:

a) broadcast connectivity: one to many;

b) point-to-point connectivity: one to one.

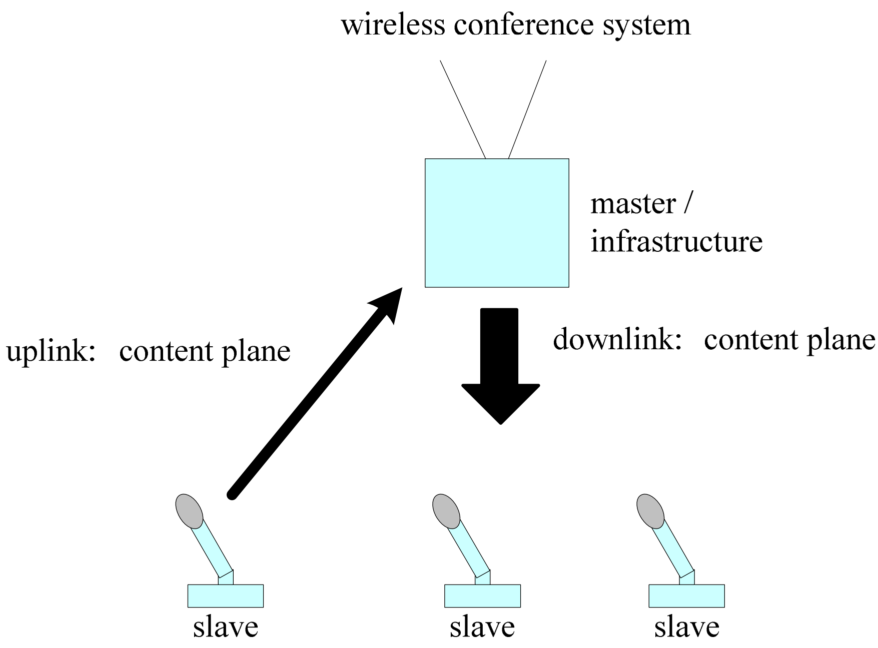

Figure 13: Terminology for wireless conference system

8.2 Usage Scenarios

In general it makes no difference in the description of the scenarios if only a small to medium system (5 to 20 audio links) or a large to very large system (40 to 200 audio links) or up to 5 systems in parallel are considered, because the cognitive process itself does not depend on the system's size but on its outcome and performance. Due to this fact, the following scenarios are only separated by their kind of interferer:

a) the static scenario characterized by continuous interference, known before starting operation;

b) the dynamic scenario characterized by temporary, unpredictable interference, which is unknown before starting operation.

8.2.1 The static scenario

The static scenario describes the case of today's PMSE system operation mode. Such PMSE contain rudimentary cognitive functionalities (e.g. scanning, frequency selection). However, we still prefer to use the term PMSE because these systems do not fully comply with the characteristics of a C-PMSE system as defined in clause 7.

Assumptions for the static scenario are:

- no unknown or unpredictable interference occurs during operation;
- all interferers have a duty-cycle of 100 %;
- the frequency allocation takes place before operation and remains unchanged during operation.

Based on these assumptions one can define several (two up to now) use cases which describe the PMSE installation and operation.

8.2.1.1 The state of the art use case

The installation and operation flow chart of this use case is depicted in figure 14.

Characteristics of the state of the art use case are:

- The PMSE acts independently of the other collocated systems and confines itself on the frequencies left free by the already installed PMSEs.
- The frequency allocation management of the PMSE usually takes care of the interference produced to the other spectrum users, depending on the regulatory environment.
- State of the art PMSE keep the signal strength of the mobile equipment unchanged during the operation. The same is assumed in the use case here. The frequency allocation is based on a worst case scenario based on the maximal power which can hit the receiver during operation.
- The PMSE assumes an equal pre-emption level for all its mobiles.

During the installation, the PMSE system fulfils three conditions depending on the number of needed audio links:

1) The national (regional) coverage: is the PMSE system able to work in the national (regional) frequency bands?
2) The local license environment: are there enough license-free frequencies for all mobiles to be used?
3) The interference environment: are there enough interference-free frequencies for all mobiles to be used?

Although the frequency allocation process may include some processing loops, they were not considered in the flowchart of figure 14 for simplicity. Such a processing loop may involve the repeated assertion of unoccupied frequencies for different frequency bands (refer to the switching range of the system where the alignment range comprises several switching ranges).

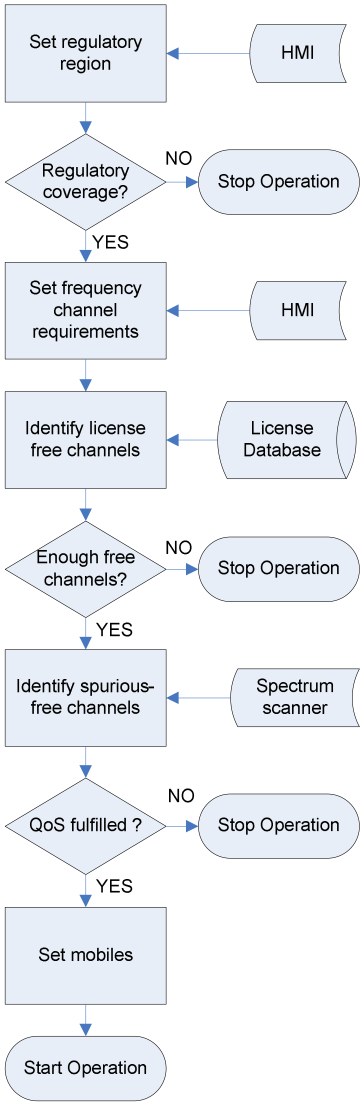

Figure 14: Use case flowchart of the static scenario

8.2.1.2 The extended use case

Based on the state of the art use case, one can envision a further development of it which will allow more audio links in a given frequency band.

The use case is based on the same assumptions as in the static scenario:

- No unknown or unpredictable interference occurs during the operation.
- The existent interferences have a steady character and 100 % duty-cycle.
- The frequency allocation takes place in the initialization process and remains unchanged during operation.

The enhancements of this use case compared to the state of the art one are:

- The PMSE systems act dependently on each other, although the initialization process takes place sequentially (one PMSE system after the other). This means that the PMSE systems are not concurrently using the frequency resources but operate in a collaborative manner. One important aspect of this characteristic is the fact that the frequency allocation logic takes notice of the already used frequencies and does not produce interferences (such as intermodulation products) on them.
- For the first enhancement to be possible, the occupied frequencies need to be identifiable, either through a radio allocation table entry or through identification patterns in their signal. This applies for all newly installed PMSE systems (after installation, frequency occupancy entries in the radio allocation table are mandatory).

- The audio link pre-emption (hierarchization) allows the differential allocation of frequency resources to audio links depending on their intended usage. For example, there may be audio links which may accept a defined level of interference (for example static conference microphones in a short distance location).
- The audio link pre-emption allows for differential allocation of signal power settings to lower the interference level (the same example as above may be used here). The signal power will however remain unchanged during the operation.

The installation and operation process is depicted in figure 15. The main element of the system is the Radio Resource Manager which contains also a subset of the national (regional) license database. The RRM contains not only information about the licensed frequencies but also about which frequencies are free on site and which are occupied. For the occupied frequencies, there may be information available about the type of signal (TV, wireless audio link, other), its pre-emption level and spurious acceptance threshold. The RRM accepts entries from all PMSE systems on site upon installation. The extent of information the RRM will deliver to the PMSE system differs on a site-by-site basis. The PMSE geo-locator (via manual setting or GPS, etc.) constitutes the basis for the resource filter which is used for information extraction and Frequency Allocation Table definition.

The second information source for the PMSE system is the frequency spectrum scanner which, as in the previous scenario, delivers "real-time" information about the spectral environment and helps identify the usable frequencies.

As in the previous use case, one may define some processing loops in the process of resource identification and optimization. They were expressly omitted in the flowchart depicted in figure 15 to improve the readability.

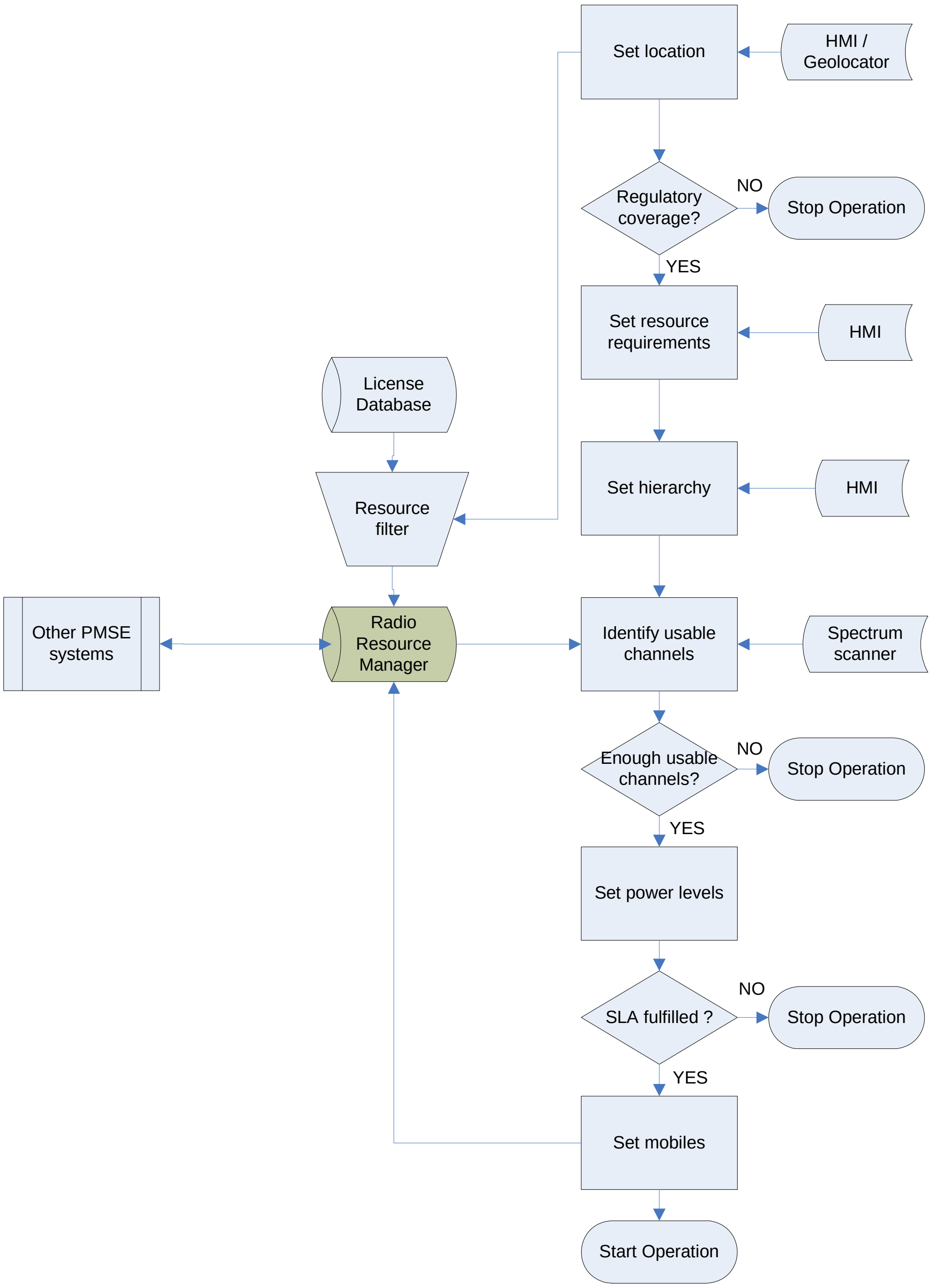

Figure 15: Use case flowchart of the extended static scenario

8.2.2 The dynamic scenario

The dynamic scenario implies the existence of interference with unpredictable behaviour and temporary nature. To cope with such an interference environment, a PMSE needs to contain cognitive functionality as defined in clause 7. Therefore, the PMSE described in this clause will be referred as a C-PMSE.

In general, the dynamic scenario can be divided into two sub-scenarios:

a) Sneaking case (figure 17): an interferer comes slowly with a predictable probability into the C-PMSE cell (e.g. an ENG team coming close to a C-PMSE)

b) Switch-on case (figure 18): a sudden, non-predictable incoming interferer disturbs the C-PMSE system (e.g. switching on a white space device), or a hidden device (e.g. hidden node comes in).

The main difference between these sub-scenarios is the reaction of the C-PMSE system being disturbed. The sneaking case allows a proactive activity because of the predictable behaviour of the interferer, whereas a reactive activity is required to counteract the switch-on case. Reactive in this context means that the quality of the audio stream falls below a certain threshold and some kind of concealment methods are used to reduce or to mask the audio interruption. Simultaneously, action has to take place at the physical layer to establish a new robust link before the concealment procedure becomes audible. In the proactive case, adaptation in the physical layer only is done without audible quality degradation before the audio stream's quality drops below the threshold. In real life it may be impossible to draw a hard line between both scenarios because depending on the ratio of the speed of the sneaking interferer to the speed of the adaptation procedure, the sneaking case will pass into the switch-on case.

Commonly, for both sub-scenarios, the static use case initialization takes place before starting operation.

In parallel to the normal operation, a sensing and classification process is running, which uses additional resources, maybe also an external frequency scanner. The result of the sensing process is used within the cognitive cycle and the RRM.

The hidden node interference describes the situation where the infrastructure does not sense an interferer which impairs the audio channel. For a conference system for example, the mobile device (receiver) may be desensitized by a white-space device situated near it, not received by the infrastructure sensing mechanism which could have triggered a defensive action.

The forward inter-modulation interference may appear at a receiver node (infrastructure or mobile device). An approaching device causes a signal strength increase at the receiving node. Two such signals may lead to inter-modulation interference with increasing strength, which may fall in a channel that was interference-free up to then. The intermodulation signal is generated in the receiver due to the nonlinearity of the RX chain.

The reverse inter-modulation interference occurs at the transmitter node (infrastructure or mobile device). Two transmitters that are closely located generate additional interference products because their signals mix in the output stages of each transmitter. This is illustrated in figure 16.

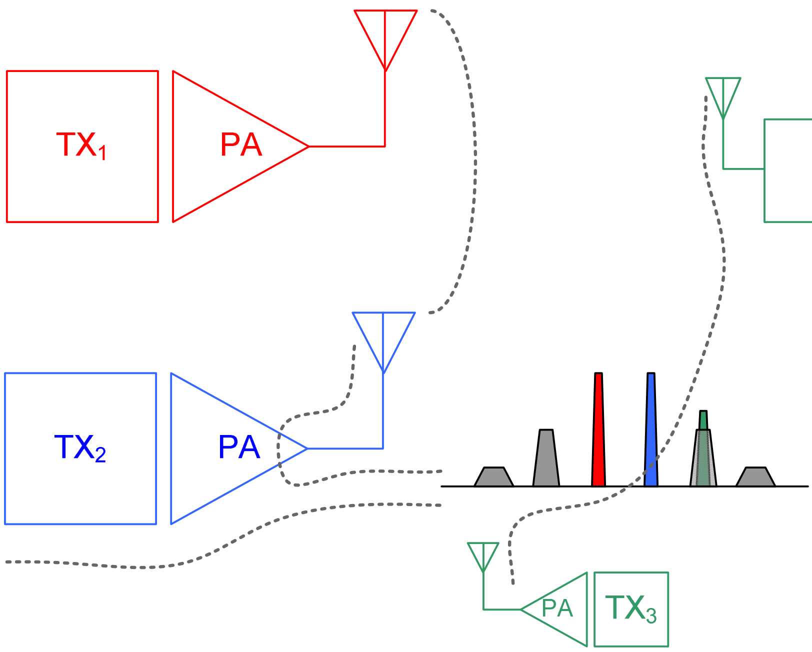

Figure 16: Reverse inter-modulation interference

The use case derived from the sneaking case is depicted in figure 17. The initialization of the C-PMSE system is performed as in the static scenario (extended use case). The cognitive cycle of this dynamic scenario is characterized by the following main procedures: **observe, understand, predict, decide and act**. The core of the cognitive cycle is the RRM which stores the current frequency occupation at the transmission location.

The observation procedure may concentrate on the audio link quality alone or on the whole frequency band interference environment depending on the C-PMSE. The use case depicted in figure 17 is based on the link quality monitoring (e.g. BER, SNR). Only if the degradation of the link quality requires it, the observation will be extended to the sensing and classification operation in order to prepare the acquisition of a new resource. The understanding process is triggered by the degradation of the signal quality, but it also may function continuously and in parallel with the signal monitoring process (as depicted in figure 17).

Any change in the resource allocation is motivated by the imminence of audible degradation of link quality. In the sneaking case, this degradation imminence is probabilistically determined and in the proactive process, a threshold of increased probability will trigger the next event. The continuous determination of degradation probability is a prediction process.

If the threshold is exceeded, new resources are negotiated for the endangered audio link. Also the RRM is informed about the registered degradation for subsequent environment analysis. The resource may be as a last resort a frequency change but not necessarily. A change in the transmission power, modulation class or coding for example may also be decided upon, depending on the interference characteristics.

The actual change of the audio link characteristic (new resource allocation) is a separate process which takes place after the resource has been negotiated and the change has been stored in the RRM tables. These changes may be also made known to the user through the performance monitor (PMO).

The learn process is an important part of any cognitive cycle but was not explicitly depicted in the use case described here. Nevertheless, the learn process is meant to support the decision and the prediction processes based on past information the system acquired along its operation, and therefore may be seen as an un-explicit part of these processes.

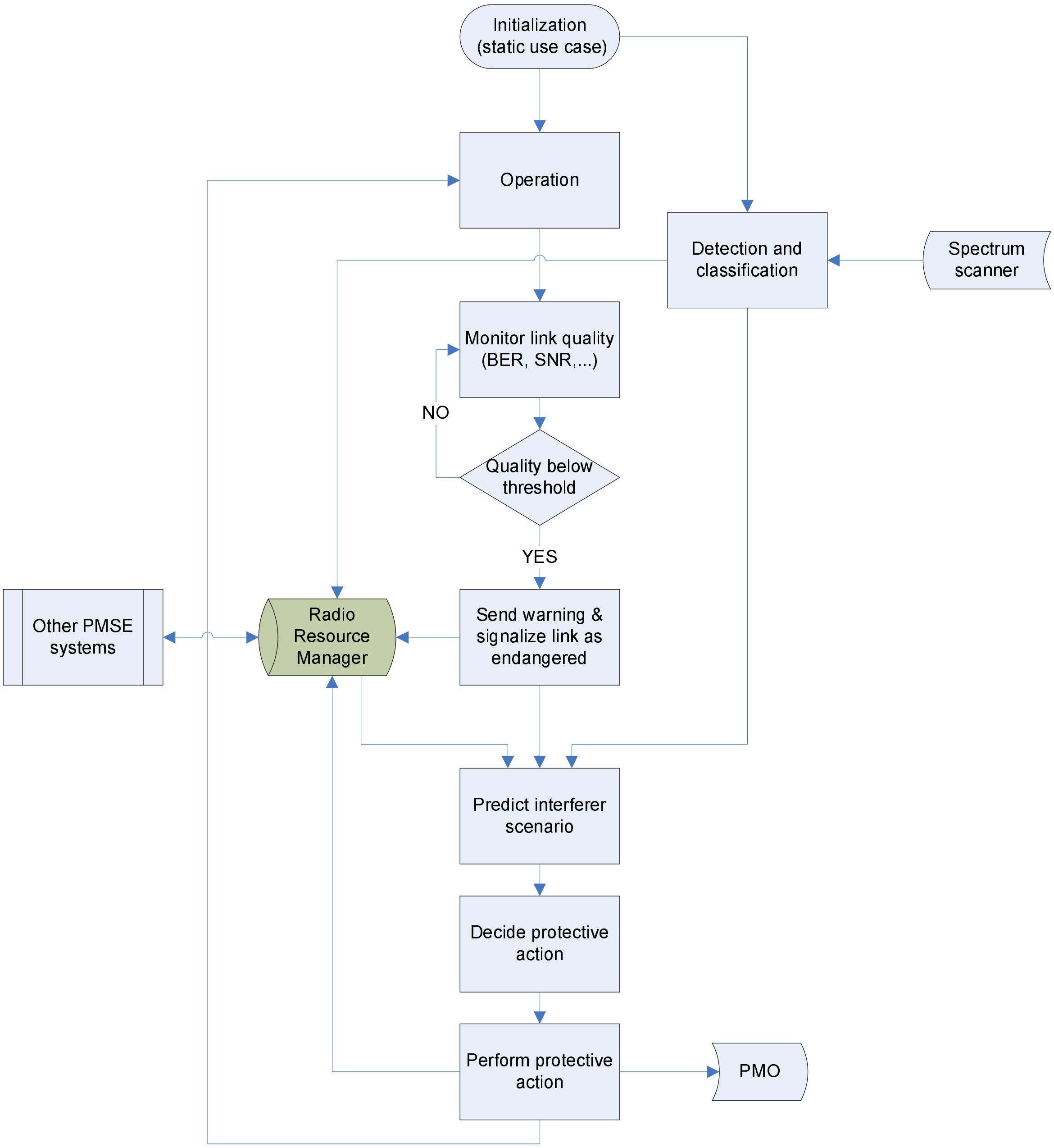

Figure 17: Use case flowchart of the sneaking sub-scenario

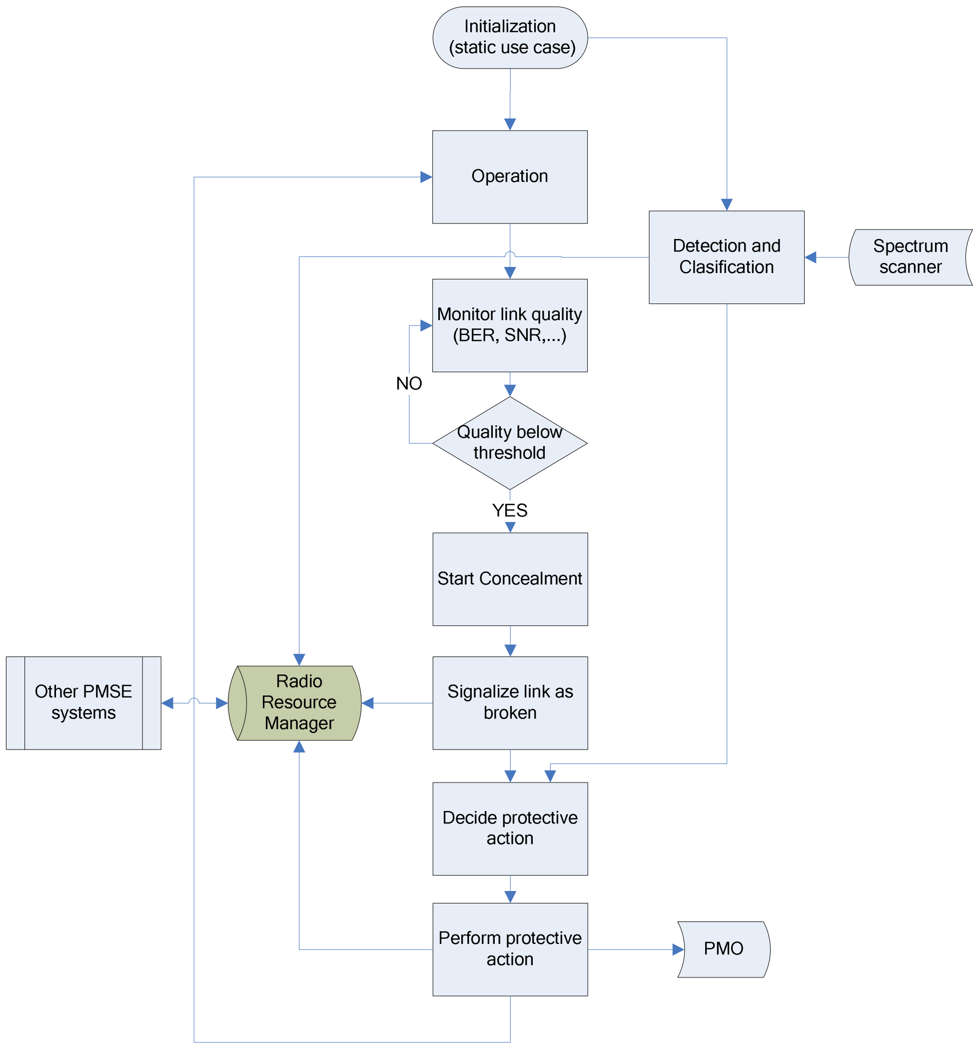

Figure 18: Use case flowchart of the switch-on sub-scenario

9 Hierarchical Database for Spectrum Management

As spectrum use grows, it is becoming increasingly important to keep track of spectrum usage. A database is a valuable spectrum management tool that could provide many benefits; especially preventing interference between users. It could also be used to help manage spectrum priority access policies. For example, in the TV bands, PMSE users are secondary to other licensed users such as television stations, but new unlicensed White Space Devices should have a lower priority than PMSE ensuring the required PMSE SLA.

The suggested approach is a hierarchical database, i.e. the amount of information being stored and frequency of database access is reduced thereby. This concept is a generic one and can be adopted by other systems as well.

9.1 The Current State of the Art

Today, PMSE frequency coordination is a manual process that is typically performed by the PMSE system installer or user. For large events there is usually a frequency coordinator in charge of all of the frequency assignments. The coordinator starts by consulting an online reference such as a regulatory or PMSE equipment manufacturer's website to determine what PMSE-channels are available for use at the event site. Next, he typically uses a software application to determine compatible frequencies in accordance with equipment and operating requirements. Such programs are available from manufacturers and software companies. If required, the coordinator obtains license(s) for the frequencies he needs. Before the event, the coordinator performs a site survey with a scanning receiver to confirm that the frequencies he intends to use are free of interference. He then sets up all of the PMSE systems on their assigned operating frequencies and tests them to be sure everything is working properly. For important events, this process is often repeated several times to be sure that nothing in the environment has changed. During the event, the PMSE coordinator monitors spectrum use and system performance and takes remedial action if any problems occur.

9.2 Structure and Architecture Proposal

Currently regulators maintain records of licensed users, e.g. TV broadcasting stations and PMSE systems. Partly this information is available online. Several regulators are currently considering how to implement spectrum databases.

In the future, it is likely that many regulators will establish electronic spectrum databases, which they will maintain directly or through independent agents. Incumbent users such as PMSE operators will be able to register their operations, and new users or devices need to ask the database before starting transmission. We refer to this process as "Ask Before Talk" (ABT).

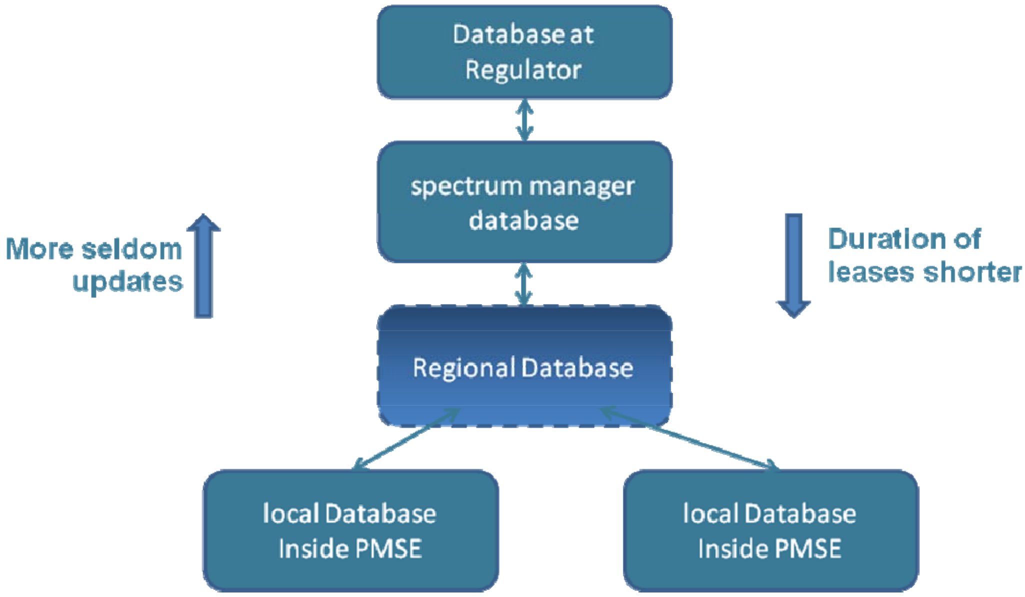

Figure 19: Hierarchical Database

The concept of a hierarchical database is proposed. It is envisioned that such a database would have several levels. The upper level would contain information from the regulatory authority in accordance with its policies. This level would connect to the regulatory database as necessary, e.g. to check for occupied frequencies or to allow the PMSE operator to register his channels/frequencies together with his location and operating dates and times to obtain protection from other users. This task would preferably be accomplished electronically by means of a machine-machine interface (mmi) between the regulatory database and the C-PMSE hierarchical database. Alternatively the PMSE user could manually enter data or make a reservation on the regulator's web site.

As described in figure 19, the middle level of the database contains information about co-located systems. The purpose of this level could be to coordinate neighbour C-PMSE system operation to help prevent interference and maintain SLAs.

The lowest level of the hierarchical database contains information about the local C-PMSE system. At a minimum it would contain a list of the frequencies and transmit power in use, but it might include additional information such as battery condition, link quality, etc. This level is always present.

9.3 Database Security and Access Methods

Concerns about security and access rights exist at the regulatory level and also at the various levels of the proposed hierarchical database structure. A regulatory database would be expected to contain significant amounts of proprietary or sensitive information. Thus, there are concerns about what information users should be able to see. For example, general database users should not be able to see who is using specific frequencies. Rather, those channels or frequency bands should simply be shown as "occupied". A user such as an event frequency coordinator might be given rights to see and manage specific frequency assignments at that location. This frequency coordinator would also be given the ability to input certain types of data, such as locations and operating frequencies. Table 4 shows possible access levels and permissions.

Table 4: Database levels

Level	Tasks	Responsible
Regulatory Level	Policies and rules	Spectrum Regulator
Spectrum Management	Provide spectrum access grants (frequency, location, time period, priority)	Spectrum Manager
Regional	Coordination of collocated systems, e.g. Inter C-PMSE	Highly Privileged User e.g. Event Coordinator
Local	Coordination of local frequencies, e.g. Intra C-PMSE	User

9.4 Database Update and Spectrum Lease

A spectrum lease is given for a limited period of time and for a specific locational area. In the IP world, the concept of DHCP leases for IP addresses has proven to be very efficient and a well established scheme.

A new lease has to be requested, if the actual lease becomes outdated or the location has changed significantly. However, a lower priority system has to perform frequent spectrum scanning for confirming the lease.

The frequency of update is controlled by the lease time in most cases.

Tendency wise, the lease duration gets shorter the lower the level of database (figure 19).

The physical access to the database may be conducted through any other access technology (e.g. fixed Ethernet, Wi-Fi, mobile network, etc.).

9.5 Database Legacy Support

The interface between the different levels of databases is typically set up as a machine-to-machine communication (M2M). However for legacy support, e.g. classical PMSE systems, web interfaces need to be offered in parallel.

9.6 Database Content

The nature of the information that could be stored in a regulatory spectrum database is currently under study by various groups. It is envisioned that such a regulatory database might contain the following information:

- location coordinates for which the information applies;
- occupied channels or frequency ranges and general user classification (e.g. TV broadcasting, PMSE, etc.);
- lease time in days, hours, and minutes (including continuous operation, e.g. broadcasting);
- specific frequencies and user data (visible only to privileged users such as the regulator and event coordinators), which could be further broken down into:
    - type of emission; i.e. emission designator with occupied bandwidth;
    - output power;
    - antenna elevation, polarization, and directional pattern;

- registered entity with contact details.

The proposed C-PMSE hierarchical database would be populated with data appropriate to each particular level. For example, the spectrum management level would incorporate data from the regulatory database as appropriate to the permissions applicable to the user. The regional level would hold data from neighbour C-PMSE systems if they are present. This data includes specific frequencies in use. Additional (optional) information might include:

- type of emission; i.e. emission designator with occupied bandwidth;
- output power;
- lease time;
- priority level;
- type of unit, e.g. body worn, handheld, or stand-alone (e.g. rack mounted);
- attenuation due to obstructions (e.g. walls) if known or present;
- sensed data (e.g. occupied or unusable channels);
- registered entity with contact details.

The local database would contain information similar to the regional level.

9.7 Location Accuracy Parameter

The location accuracy is dependent on the database level. The higher the level, the less accurate the information.

Existing example: ITU specifies three world regions, while national regulatory bodies define smaller regions such as a town or a venue. The local database might define only a building or a room.

For fixed users, such as television broadcasting stations, the location information is known with a high degree of precision, but for mobile users, it is determined by some other means. Regulatory bodies such as OFCOM (U.K.) and the FCC (U.S.) are contemplating a location accuracy requirement on the order of 50 meters. This is quite sufficient for high powered transmitters that have a large footprint, such as television broadcasting stations, which cover tens or even hundreds of kilometres. However, it is potentially problematic for PMSE systems, which typically have a working range of only about 100 meters. Thus, a potentially interfering TVBD could be within the interference range of a PMSE system due to the error margin in determining its location. One work-around that has been suggested to overcome this problem is to have the PMSE user define the operating area for his system by entering multiple coordinates in the regulatory database. The location accuracy issue could also be a problem for inter-PMSE coordination situations. Thus, the distance between neighbouring PMSE systems might need to be entered manually.

Geolocation is the primary location determining technology being considered to date, but it has some limitations. The Global Positioning System (GPS) is a U.S. based system, which may not be acceptable to European administrations. The European Galileo system may be a suitable alternative when it becomes available. However, both systems have problems when used indoors, since satellite signals are typically not receivable inside buildings. One possible work-around involves placing a satellite receiver at a nearby outdoor location and relaying the location information to the C-PMSE system using a wired or wireless LAN connection. However, this may pose logistical problems. Other technical solutions may exist, such as using mobile system signals or broadcast signals to determine the location of a PMSE system. Other technologies for indoor geolocation are WLAN, RFID and UWB.

10 RF parameters of PMSE Audio services and quality service levels

These categories need to be specified in detail:

SLA:

- Audio Latency;
- Audio Interrruption;
- Audio Quality;
- Audio Bandwidth;
- Audio Source Coding (Compander or Codec).

RRM

- RF carrier frequency;
- RF bandwidth;
- RF power;
- Modulation and Channel Coding.

11 Conclusions and Recommendations

This clause summarises the findings so far. These need to be confirmed by means of practical verification.

11.1 Hidden Node Problem / "Ask Before Talk"

The PMSE systems would be vulnerable to the hidden node problem. The location of PMSE receivers cannot be detected by spectrum sensing techniques, but receivers are protected to ensure the high audio quality demand. "Listen Before Talk" (LBT) and spectrum sensing are not sufficient for protection. Instead it is proposed to go for a regime of "Ask Before Talk" (ABT), where some combination of local and hierarchical databases on spectrum use (frequency, power, location, time) is queried.

The database being queried cannot be constructed by spectrum sensing techniques only, as the spectrum sensing technique cannot provide sufficient information on the location of receivers.

In conclusion, these techniques will not provide sufficient protection for PMSE systems.

11.2 Intermodulation

Receiver and transmitter intermodulation are effects that cannot be neglected with frequency allocation. The view of a pool of uncoupled orthogonal radio resources is wrong. Cognitive radio techniques have to take into account spurious mixing products that may interfere with other services.

In conclusion, intermodulation should be considered when allocating spectrum.

11.3 Interference Power

It is concludes that maximum tolerable interference power should not be defined independent of the bandwidth used, as it makes a difference whether an PMSE system with RF bandwidth of 200 kHz is hurt by a 200 kHz or a 5 MHz wide interferer.

It is recommended that PSD be the preferred method for defining the interference power.

11.4 Compatibility of cognitive devices in the 470 MHz to 862 MHz band

Because of the hidden node problem, it is concluded that all CDs also have to follow the regime of "Ask Before Talk". If CDs would only follow a regime of "Listen Before Talk", protection of PMSEs cannot be ensured.

It is recommended that Ask before talk (ABT) be investigated for use within this band.

11.5 Interference by CDs

There are risks that operation of several CDs might generate spurious mixing products that interfere with PMSE systems. Therefore the frequency allocation of CDs are coordinated with the frequency allocation by PMSE systems and TV stations.

This would be very difficult to archive at a practical level. It is recommended that this area be further investigated.

11.6 Propagation and Interference characteristics

With the flexible use of spectrum, agreed propagation and interference models should be produced in order for designers of equipment and administrations to have a common database to work from. This database should obtain information from the various CEPT and ECC reports and as a minimum include:

- body loss / body absorption;
- wall absorption / house absorption;
- fading characteristics.

It is recommended to contact ECC with a view developing this database.

11.7 QoS Monitoring

It is concluded that for rating the quality of an analogue FM link, field strength (RSSI) is not a sufficient metric, as it covers signal plus interference power. However, audio quality is severely degraded if the co-channel interference level is high (C/I). A measure is needed to rate the audio quality in situ during operation. A measure for audio quality is derived and offered to the C-PMSE to perform its optimization.

Present methods of measuring QoS for existing FM systems rely on the power of the RF signal received; for the new cognitive digital systems, this an imprecise method of measuring QoS.

A new method of measuring QoS for digital systems should be produced which will include the measurement of audio quality.

It is recommended that a QoS measurement be investigated and defined for C-PMSE.

11.8 Spectral efficiency

Considering clause 4.10, it can be shown that existing PSME systems are spectrally efficient when compared with other mobile systems. Changing from analogue FM systems to digital C-PSME will not in itself reduce spectrum demand. Further work is required to define methods of increasing spectral efficiency of PSME.

It is recommended that further work be done to investigate techniques for spectral efficiency.

11.9 Radio Resource Management

Radio Resource Management techniques were found as a valuable tool to enhance spectral efficiency and ensure meeting the SLAs.

In conclusion, RRM is part of future work of C-PSME.

11.10 Hierarchical Database

Considering clause 9, the use of database information will greatly assist a range of issues.

It is recommended that the use of databases be investigated in conjunction with the ECC.

11.11 Geolocation accuracy

The greater the accuracy of the geolocation system, the better spectral efficiency can be obtained.

It is recommended to investigate the best and most practical geolocation system for these devices.

11.12 Database security

There are concerns whether the usage of databases to manage radio resources has security or privacy related issues. The databases provide in-depth knowledge on the locations of transmitters and receivers. Management of access rights for read and write operation is a critical task.

A database showing the location of PMSE devices will be commercially sensitive, and every effort must be made to ensure security of this information.

It is recommended that those considering the database issue should take into account the commercial sensitivity of this information.

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History

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