ETSI TR 103 067 V1.1.1 (2013-05)

Reconfigurable Radio Systems (RRS);
Feasibility study on Radio Frequency (RF) performance for Cognitive Radio Systems operating in UHF TV band White Spaces

Reference

DTR/RRS-01008

Keywords

CRS, GLDB, performance, UHF, white space

ETSI

650 Route des Lucioles
F-06921 Sophia Antipolis Cedex - FRANCE

Tel.: +33 4 92 94 42 00 Fax: +33 4 93 65 47 16

Siret N° 348 623 562 00017 - NAF 742 C
Association à but non lucratif enregistrée à la
Sous-Préfecture de Grasse (06) N° 7803/88

Contents

Intellectual Property Rights

IPRs essential or potentially essential to the present document may have been declared to ETSI. The information pertaining to these essential IPRs, if any, is publicly available for **ETSI members and non-members**, and can be found in ETSI SR 000 314: *"Intellectual Property Rights (IPRs); Essential, or potentially Essential, IPRs notified to ETSI in respect of ETSI standards"*, which is available from the ETSI Secretariat. Latest updates are available on the ETSI Web server (http://ipr.etsi.org).

Pursuant to the ETSI IPR Policy, no investigation, including IPR searches, has been carried out by ETSI. No guarantee can be given as to the existence of other IPRs not referenced in ETSI SR 000 314 (or the updates on the ETSI Web server) which are, or may be, or may become, essential to the present document.

Foreword

This Technical Report (TR) has been produced by ETSI Technical Committee Reconfigurable Radio Systems (RRS).

1 Scope

The present document aims to identify the relevant Radio Frequency (RF) scenarios and RF performance applicable to:

- Cognitive Radio Systems (CRS) for the coexistence between CRSs when they are operating in UHF TV band White Spaces.
- Both broadcasting service and Cognitive Radio Systems for the deployment of CRS in the UHF TV band White Spaces when advanced incumbent protection techniques and implementations such as cooperative sensing and advanced geo-location database are considered.
- Both broadcasting service and Cognitive Radio Systems for the coexistence studies in UHF TV band White Spaces in regions outside of CEPT responsibility.

The scenarios described in the preset document are based on [i.22] and [i.3].

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 referenced 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] FCC 10-174: "Second Memorandum Opinion and Order", Sept. 23, 2010.

[i.2] OFCOM, Consultation on license-exempting cognitive devices using interleaved spectrum, Feb. 2009.

[i.3] ECC Report 159 (January 2011): "Technical and Operational Requirements for the Possible Operation of Cognitive Radio Systems in the 'White Spaces' of the Frequency Band 470-790 MHz".

[i.4] IEEE 802.22 (2011): "Standard for Wireless Regional Area Networks. Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Policies and procedures for operation in the TV bands".

[i.5] IEEE 802.11n (2009): "IEEE Standard for Information technology. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications".

[i.6] Recommendation ITU-R P.1546-4 (October 2009): "Method for point-to-area predictions for terrestrial services in the frequency range 30 MHz to 3 000 MHz".

[i.7] IEEE Communications Letters, Vol. 14, no. 10, pp. 886-888, October 2010: "Orthogonal multiplexing in a subspace of frequency well-localized signals", Jaap van de Beek.

[i.8] IEEE Transactions on Communications, Vol. 54, no. 12, pp. 2173-2185, December 2006: "Spectrally precoded OFDM", Char-Dir Chung.

[i.9] IEEE Communications Letters, Vol. 10, no. 6, pp. 444-446, June 2006: "Subcarrier weighting: a method for sidelobe suppression in OFDM systems", Ivan Cosovic, Sinja Brandes, Michael Schnell.

[i.10] IEEE Communications Letters, Vol. 13, no. 12, pp. 881-883, December 2009: "Sculpting the multicarrier spectrum: a novel projection precoder", Jaap van de Beek.

[i.11] IEEE Transactions on Communications, Vol. 59, no. 3, pp. 844-853, March 2011: "Optimal orthogonal precoding for power leakage suppression in DFT-based systems", Meng Ma, Xiaojing Huang, Bingli Jiao and Y. Jay Guo.

[i.12] ETSI TS 136 211: "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation (3GPP TS 36.211)".

[i.13] Proc. First European Conference on Antennas and Propagation (EuCAP), November 2006: "Deterministic propagation prediction method developed by the European broadcasting union", R. Grosskopf.

[i.14] ERC Report 85: "Compatibility Analysis of Radio Astronomy in the Frequency Range 608-614 MHz within DVB-T".

[i.15] CEPT Chester 97: "The Chester 1997 Multilateral Coordination Agreement relating to Technical Criteria, Coordination Principles and Procedures for the introduction of DVB-T".

[i.16] ETSI TS 136 101 (V10.6.0): "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception (3GPP TS 36.101 version 10.6.0 Release 10)".

[i.17] ETSI TS 136 104: "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) radio transmission and reception".

[i.18] IEEE International Conference on Communications, June 2006, Vol. 4, pp. 1658-1663: "Cooperative Sensing Among Cognitive Radios", S.M. Mishra, A.Sahai, and R.W. Brodersen.

[i.19] IEEE Signal Processing Letters, vol. 15, pp. 649-652, 2008: "Blindly combined energy detection for spectrum sensing in cognitive radio", Y. H. Zeng, Y.-C. Liang, and R. Zhang.

[i.20] ETSI EN 300 744 (V1.6.1) (01-2009): "Digital Video Broadcasting (DVB); Framing structure, channel coding and modulation for digital terrestrial television".

[i.21] Wenshan Yin, Pinyi Ren, Jun Cai and Zhou Su. A pilot-aided detector for spectrum sensing of Digital Video Broadcasting-Terrestrial signals in cognitive radio networks. Wireless Communications and Mobile Computing 2011.

[i.22] ETSI TR 102 907: "Reconfigurable Radio Systems (RRS); Use Cases for Operation in White Space Frequency Bands".

[i.23] ECC Report 186 (January 2013): "Technical and operational requirements for the operation of WSDs under geo-location approach".

[i.24] Document Number D2.2 Scenario Definitions, Project: Flexible and Spectrum Aware Radip Access through Measurements and Modeling in Cognitive Radio Systems (FARAMIR).

[i.25] Recommendation ITU-R M.2241 (11/2011): "Compatibility studies in relation to Resolution 224 in the bands 698-806 MHz and 790-862 MHz".

[i.26] Electrical Engineering and Computer Sciences, University of California at Berkeley/Technical Report No. UCB/EECS-2009-3, "How much white space is there".

NOTE: Available at http://www.eecs.berkeley.edu/Pubs/TechRpts/2009/EECS-2009-3.html.

[i.27] ETSI TR 136 942: "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Frequency (RF) system scenarios (3GPP TR 36.942)".

[i.28] IEEE 802.11af: "IEEE Standard for Information technology--Telecommunications and information exchange between systems Local and metropolitan area networks--Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications-- Amendment 4: TV White Spaces Operation-D2.0".

[i.29] IEEE 802.11: "IEEE Standard for Information technology--Telecommunications and information exchange between systems Local and metropolitan area networks--Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications".

[i.30] IEEE 802.11ac: "IEEE Standard for Information technology--Telecommunications and information exchange between systems Local and metropolitan area networks--Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications-- Amendment 4: Enhancements for Very High Throughput for Operation in Bands below 6 GHz-D5.0".

[i.31] ECMA 392: "MAC and PHY for Operation in TV White Space".

[i.32] 3GPP TR 36.814: "Evolved Universal Terrestrial Radio Access (E-UTRA); Further advancements for E-UTRA physical layer aspects".

[i.33] IEEE 802.11g: "IEEE Standard for Information technology--Telecommunications and information exchange between systems Local and metropolitan area networks--Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications-- Amendment 4: Further Higher Data Rate Extension in the 2.4 GHz Band-2003".

3 Definitions and abbreviations

3.1 Definitions

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

cognitive radio: radio, 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 and autonomously adjust its operational parameters and protocols according to this knowledge in order to achieve predefined objectives, e.g. more efficient utilization of spectrum; and
- to learn from the results of its actions in order to further improve its performance.

program making and special events: equipment that is used to support broadcasting and special events in general

NOTE 1: Special events include culture events, concerts, sport events, conferences, trade fairs, etc.

NOTE 2: These devices operate in different frequency bands. In the present document we focus on devices using the band 470 MHz - 862 MHz, also referred to as professional wireless microphone systems.

radio system: system capable to communicate some user information by using electromagnetic waves

NOTE: Radio system is typically designed to use certain radio frequency band(s) and it includes agreed schemes for multiple access, modulation, channel and data coding as well as control protocols for all radio layers needed to maintain user data links between adjacent radio devices.

silent period: period of time during which a radio system or a subset of devices in a radio system abstain from any transmission (data, control, reference, etc) over a particular band or channel

NOTE: Silencing refers to the act of a device or set of devices to create a silent period.

white space: part of the spectrum, which is available for a radiocommunication application (service, system) at a given time in a given geographical area on a non-interfering/nonprotected basis with regard to primary services and other services with a higher priority on a national basis.

3.2 Abbreviations

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

ACIR	Adjacent Channel Interference Ratio
ACLR	Adjacent Channel Leakage Ratio
ACS	Adjacent Channel Selectivity
AP	Access Point
ATSC	Advanced Television Systems Committee
AWGN	Additive White Gause Noise
BLER	Block Error Rate
BS	Base Station
BW	Band Width
CCA-ED	Clear Channel Assessment Energy Detection
CCDF	Complementary Cumulative Distribution Function
CCE	Control Channel Element
CCP	Central Control Point
CDF	Cumulative Distribution Function
CEPT	Commission of European Post and Telecommunications
CG	Coexistence Gap
CIR	Carrier to Interference Ratio
CMMB	China Multimedia Mobile Broadcasting
CNR	Carrier to Noise Ratio
CP	Cyclic Prefix
CQI	Channel Quality Indication
CQI_{AVG}	Average Channel Quality Indication
CR	Cognitive Radio
CRC	Cycle Redundancy Check
CRS	Cognitive Radio System
CSMA	Carrier Sense Multiple Access
DB	Database
DCI	Downlink Control Information
DL	Down Link
DRX	Discontinuous Reception
DTMB	Digital Terrestrial Television Multimedia Broadcasting
DTT	Digital Terrestrial Television
DTV	Digital Television
DVB-T	Digital Video Broadcasting-Terrestrial
ECC	Electronic Communications Committee
EIRP	Effective Isotropic Radiated Power
ERP	Effective Radiated Power
ETU	Extended Typical Urban
EVM	Error-Vector-Magnitude
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
FFT	Fast Fourier Transform
GAP	Gap
GD	Guard Duration
GI	Guard Interval
GLDB	Geo-Location Database
GNSS	Global Navigation Satellite System
GP	Guard Period
HARQ	Hybrid Acknowledge Request
HW	Hardware
HW/SW	Hardware/Software
ICIC	Inter Cell Interference Coordination
I_{DTT}	Interference from the DTT system

IFFT	Inverse Fast Fourier Transform
IM	Interference Margin
ISD	Inter Site Distance
ISDB	Integrated Services Digital Broadcasting
ISM	Industrial Scientific and Medical (frequency band)
ITU-R	International Telecommunication Union - Radio
KW	Kilo-Watt
LE	License Exempt
LOS	Line of Sight
LP	Location Probability
LTE-CR	Long Term Evolution-Cognitive Radio
MAC	Medium Access Control
MBSFN	Multicast/Broadcast over a Single Frequency Network
MCH	Multicast Channel
MET	Maximum Eigen-value to Trace
MHz	Mega Hertz
MI	Multiple interference
MME	Mobility Management Entity
MS-BS	Mobile Station/Base Station
OFCOM	Independent regulator and competition authority for the UK communications industries
OFDM	Orthogonal Frequency Division Multiplexing
OPNET	A tool for application and network performance management
PA	Power Amplifier
PC	Power control
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Dedicated Shared Channel
P_{DTT}	Transmit power of the DTT broadcast station
PHY	Physical Layer
P_I^{IM}	Transmit power of the Interference Monitoring
P_I^{PE}	Transmit power of the WSD based on the propagation estimation
PL_{DTT}	Path loss of DTT
PN	Pseudo Noise
PRBS	Pseudo-Random Binary Sequence
PSD	Power Spectral Density
QP	Quiet Period
QPSK	Quadrature Phase Shift Keying
RAT	Radio Access Technology
REG	Resource Element Group
RF	Radio Frequency
RRC	Radio Resource Control
RRM	Radio Resource Management
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RX	Reception
SINR	Signal to Interference plus Noise Ratio
SISO	Single Input Single Output
SM	Safety Margin
SNR	Signal to Noise Ratio
SRS	Sounding Reference Signal
STA	Station
SVD	Singular Value Decomposition
TA	Timing Advance
TB	Technical Board
TDD	Time Division Duplex
TD-LTE	Time Division Long Term Evolution
TDM	Time Division Multiplex
T_{GP}	the length of guard period
TOFF	Period of no transmission
TON	Period of transmission
TRX	Transmitter-Receiver
TS	Technical Specification
TTT	Time To Trigger

TV	Television
TVWS	Television White Space
TX/RX	Transmitter-Receiver
UE	User Equipment
UHF	Ultra High Frequency (300 Mhz - 3 000 Mhz)
UL	Up link
UL/DL	Up link/Down link
UTRA	Universal Terrestrial Radio Access
VS	Versus
Wi-Fi	Wireless Local Area Network product certified by Wi-Fi Alliance
WLAN	Wireless Local Area Network
WM	Wireless Microphone
WRAN	Wireless Regional Area Network
WS	White Space
WSD	White Space Device

4 Advanced incumbent protection techniques and implementations

4.1 Advanced sensing techniques

4.1.1 General

Sensing has been considered as one kind of protection technique by regulatory bodies in order to protect incumbents from Cognitive Radio Systems which may opportunistically use the UHF TV band WS. Sensing has the following advantages:

1) It can be used by devices that are unable to access a geo-location database. One example of such a device is the so called "sensing only device" as described in the FCC Second Memorandum Opinion and Order [i.1].

2) It can be used to improve protection of the incumbent compared to geo-location database use only.

3) It can be used to find further opportunities for use of WS beyond what is available in the geo-location database.

A large degree of study has been done on sensing algorithms in the literature. The main property of any sensing algorithm remains the sensitivity, i.e. the minimum incumbent signal power that it can detect reliably in noise with the required probability of detection and false alarm. Regulatory bodies have defined minimum sensitivity requirements for incumbent protection in the WS:

- Federal Communications Commission (FCC):
  - The FCC requires that TV band devices be capable of sensing analog and digital TV signals at a level of -114 dBm within defined receiver bandwidths. It also requires that TV band devices be capable of sensing wireless microphone signals at a level of -107 dBm [i.1].
- Commission of European Post and Telecommunications (CEPT)
  - CEPT presents sensitivity threshold calculations which yield detection thresholds which depend on the WSD characteristics, deployment scenarios, and BS/receiver configurations. The thresholds calculated by CEPT range from -155dBm to -91 dBm [i.3]. OFCOM UK, for instance, has set the minimum sensitivity for TV signal and wireless microphone signal detection to -114 dBm and -126 dBm respectively [i.2].

Detection of incumbent users through sensing poses several challenges:

- Detection of incumbents at the sensitivity levels required by regulatory bodies requires considerably complex sensing hardware that may not be feasible or economical for most wireless devices which will use the TV bands.

- The effect of multipath and shadowing further complicates incumbent detection. When the sensing node exhibits multipath and shadowing, the required sensitivity of the algorithm will become unreasonably large.
- Identification of incumbents through sensing when other WSDs are transmitting can result in the need for feature detection algorithms which can be difficult, and in some cases not feasible.

4.1.2 Cooperative Sensing

In cooperative sensing, multiple sensing nodes perform the task of detection of an incumbent and the detection decision is made based on the fused results of each node. The main motivation behind cooperative sensing is to lighten the burden of sensing that a single sensing node would need to carry by distributing the detection among multiple nodes. When a single node exhibits multipath or shadowing and therefore has higher sensitivity requirements on its sensing algorithm, cooperative sensing can be used to effectively decrease the sensitivity requirements by relying on other nodes which may not exhibit these same unfavorable conditions.

Efficient cooperative sensing requires:

- Exploiting information from each of the sensing nodes to effectively choose the nodes that will be involved in the detection task. This could include location, relative signal correlation, etc.
- Effectively dividing the sensing task based on factors such as minimizing power consumption and properly exploiting the sensing capabilities of each node.
- Coordinating the location and method in which the fusion of sensing results from the individual nodes is performed.

4.1.2.1 Use of Correlation Information in Cooperative Sensing

In spectrum sensing, if a particular node is experiencing a multipath fade or shadowing at a particular moment or geographical location, it is sensing requirements are suddenly much more stringent since that node needs to detect the presence of a primary user at a power level that is now much lower than just the path loss from the primary user to the node in question. As a result, the sensing requirements (also known as sensitivity) of the sensing algorithm may become unreasonably large when considering that sensing is performed in a time shared fashion with actual data transmission. The problem of requiring a sensing node to be able to handle the worst-case signal attenuation that may arise due to the presence of multipath or shadowing could be alleviated through cooperative sensing. If multiple nodes are involved in the sensing decision, then the fact that a particular node is in a fading situation could be offset by the sensing information of another node which may be in a more favourable fading environment. By merging or fusing the decisions between these nodes, the required sensitivity for each of the nodes can effectively be decreased.

Figure 1 illustrates the decrease in sensitivity with cooperative sensing under different fading conditions [i.18]. As the number of users is increased, the required sensitivity of the sensing devices decreases and approaches the path loss. In a practical system, however, the number of users is limited and only a limited amount of gain can be achieved through cooperative sensing. As figure 1 illustrates, the gain per additional user is greater in the case of multipath fading only. This happens as multipath at different radios is generally uncorrelated since a small change in distance between the radios will result in loss of correlation. On the other hand, shadowing results in high correlation if two radios are blocked by the same obstacle. For this reason, the case of shadowing shows less gain on average as the number of nodes is increased.

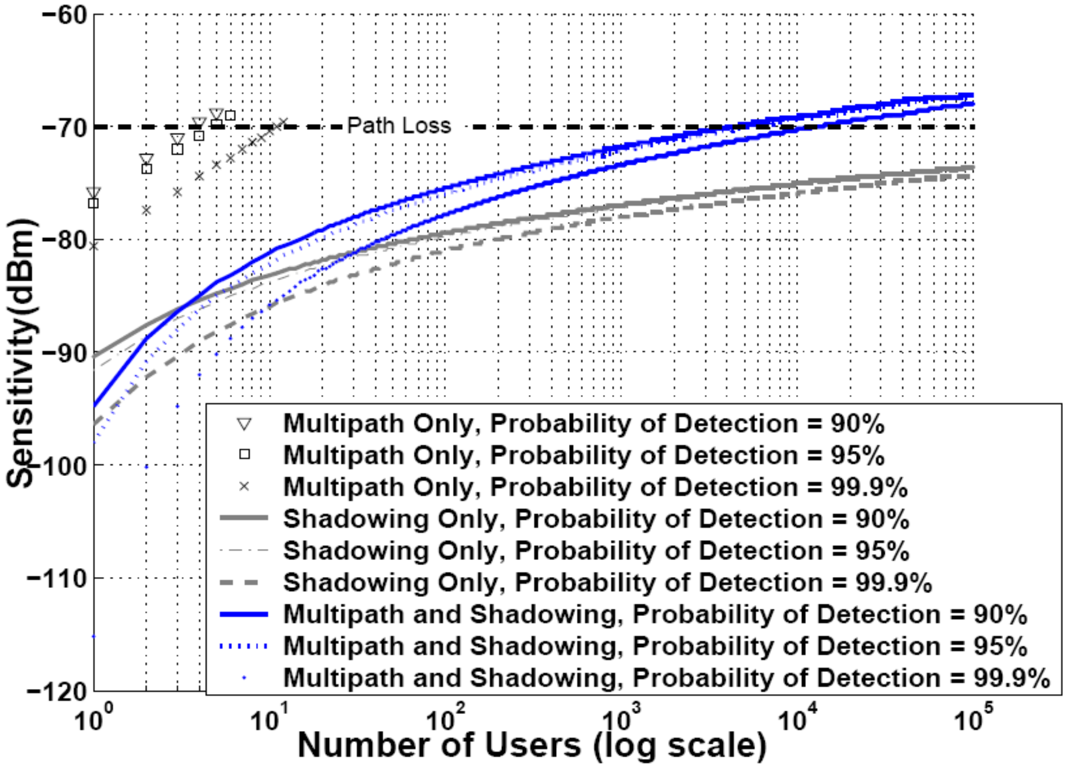


Figure 1: Sensitivity Increase with Cooperative Sensing [i.18]

In cooperative sensing, generally a central fusion node performs fusion of sensing information coming from different sensing nodes. In order for fusion of sensing information to result in a better estimate of the presence of a primary user and thus decrease the required sensing sensitivity of the individual sensing nodes, the fusion node can ensure that the sensing information received from each CR node is uncorrelated. This means that two nodes providing sensing information or sensing decisions should not both be located simultaneously in a fade with respect to the primary user. As long as each additional sensing node which contributes to the cooperative sensing decision is uncorrelated with the others, adding the information from additional sensing node increases the performance of the fused decision made by the fusion node.

A sensing scheme which uses correlation information to tailor its cooperative sensing can consist of two phases:

1) an initial phase of correlation determination whereby the central fusion collects information to determine the correlation between the nodes; and

2) a sensing and fusion phase whereby sensing is scheduled and fusion is performed based on the information obtained from the initial phase.

The initial phase may be repeated continuously based on the size of network, the expected mobility of sensing nodes, and the frequency in which the actual sensing is performed.

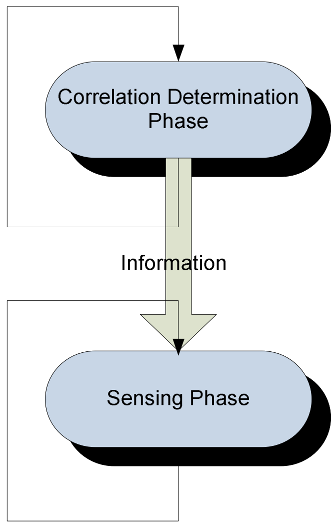


Figure 2: Two stage approach for cooperative sensing

An initial phase of determining the users which are uncorrelated in the network can be performed using sensing information received during periodic sensing periods. This information can consist of coarse sensing information (such as a power spectral density over a wide bandwidth) which can also be used for the purpose of actual sensing. Other methods can also be used to collect the coarse sensing information that is used for correlation determination.

Each sensing node sends sensing information to the fusion node periodically. The fusion node will use this sensing information to determine which of the nodes in the network are uncorrelated so that future information from uncorrelated nodes can be used for fusion. In addition, when two nodes are determined to be correlated, future sensing tasks performed by these nodes can be divided so as to achieve faster sensing for a particular set of channels, or battery savings for the correlated nodes which can share the sensing load for a set of channels. As a result, the correlation information obtained from the correlation determination stage could be used to determine:

- Which users' sensing results should be combined/fused to obtain a single decision about the presence or absence of a primary user on a particular channel.
- Which users should instead cooperate in order to split the sensing task over multiple channels and assign each user a subset of the channels.

The flowchart in figure 3 shows a possible sequencing of events in the two stage cooperative sensing scheme where the correlation information is collected in the initial sensing operation.

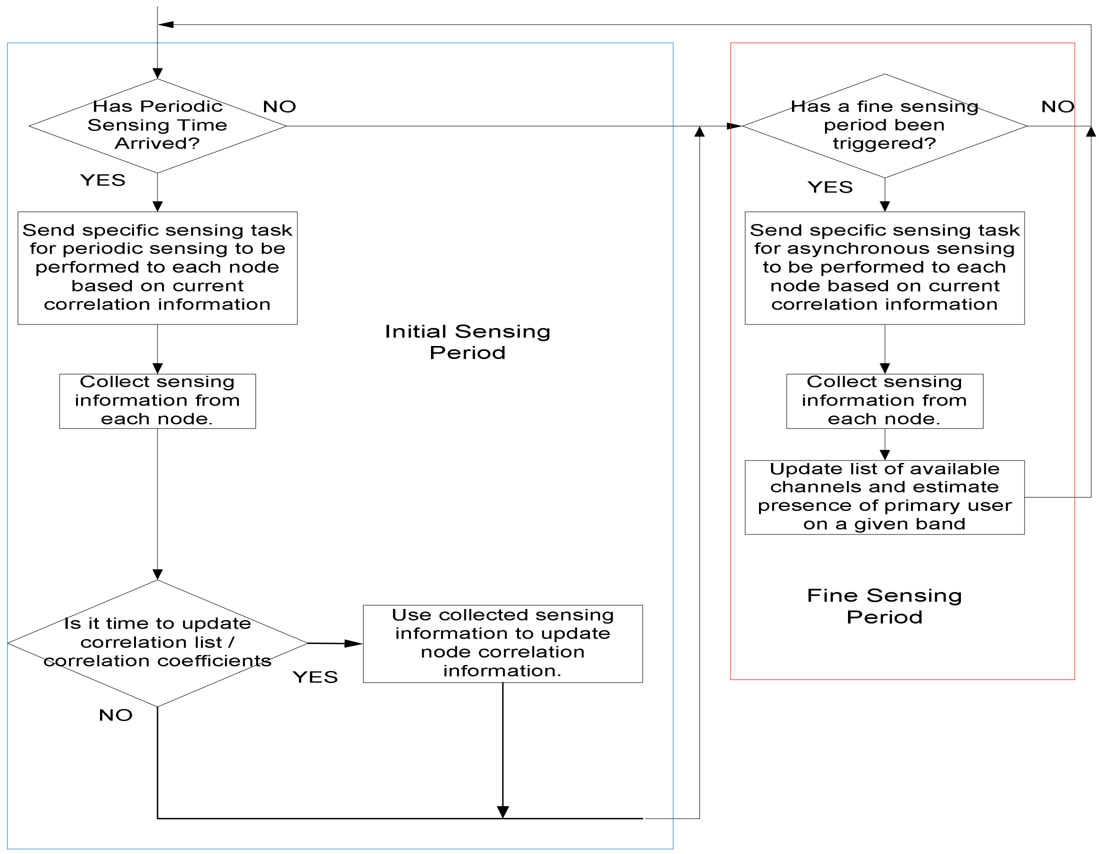


Figure 3: Flow diagram of Potential Two-Stage Cooperative Sensing Scheme

Several challenges exist with the two-stage cooperative sensing scheme, including:

- Determining how often to perform the initial step and dealing with mobility (the scheme may not be suitable for high mobility cases but could be used in fixed sensor networks operating in TVWS).
- Determining the algorithm for correlation determination.

4.1.3 Event Driven Sensing

In order to make use of the UHF TV band WS, sensing devices will need to periodically perform these sensing operations while the WS is being used for data communication. The period of sensing operation should be a tradeoff between power consumption for the sensing devices and the agility of the network to leave the WS frequencies occupied by a newly arriving incumbent. One method to improve agility is to make use of events to trigger non-periodic (or asynchronous) sensing. The occurrence of an event can be communicated to the sensing nodes to trigger a non-periodic sensing occasion. These events could, for example, be relative to the change in performance of a network (e.g. a drop in CQI) which may indicate the immediate need for sensing to determine whether an incumbent is present.

In event driven sensing, it is assumed that a "Central Control Point (CCP)" controls, configures, and manages one or many WS devices. Sensing done in the WS devices is triggered by the CCP when certain conditions are met. Compared to continuous or periodic sensing, event driven sensing is only performed following the occurrence of a specific event. This procedure has the advantage of conserving battery power (as the sensing frequency may be reduced) and improving throughput (as the actual sensing time and the amount of silencing periods may be reduced).

While event driven sensing may not replace periodic sensing that is required by some regulations such as the FCC (in the case of sensing only devices under this regulation), it may serve as a complementary method to speed up detection of an incumbent when it is expected that the incumbent will generate with strong enough transmit power when it takes control of the channel. The periodic sensing performed on the channel can be done with the minimum frequency allowed to satisfy the regulations, and event driven sensing can complement the periodic sensing to quickly detect an incumbent and evacuate the channel when the appearance of that incumbent occurs between two scheduled periodic sensing events.

Alternatively, event driven sensing can be used as the only mechanism for detection of another system in the case where there are no regulations or less stringent regulations for detection. For example, in the case of coexistence with another secondary system, the WS CRS in question may want to detect the presence of another secondary system operating on the same channel. In this case, it would rely entirely on event driven sensing (without the need to perform periodic sensing) in order to know when another secondary system arrives on the same WS channel. This would realize savings in power and throughput for the WS CRS, which would be able to determine the arrival of another secondary system without the need to perform periodic sensing.

The following flow chart describes the event driven sensing procedure. The procedure is based on the configuration and measurement of certain key quantities by the WS devices while these devices perform regular TX/RX operations. When one or more WS devices detect an inconstancy in their measurements, they notify the CCP of this by reporting this event. The steps are enumerated and described below.

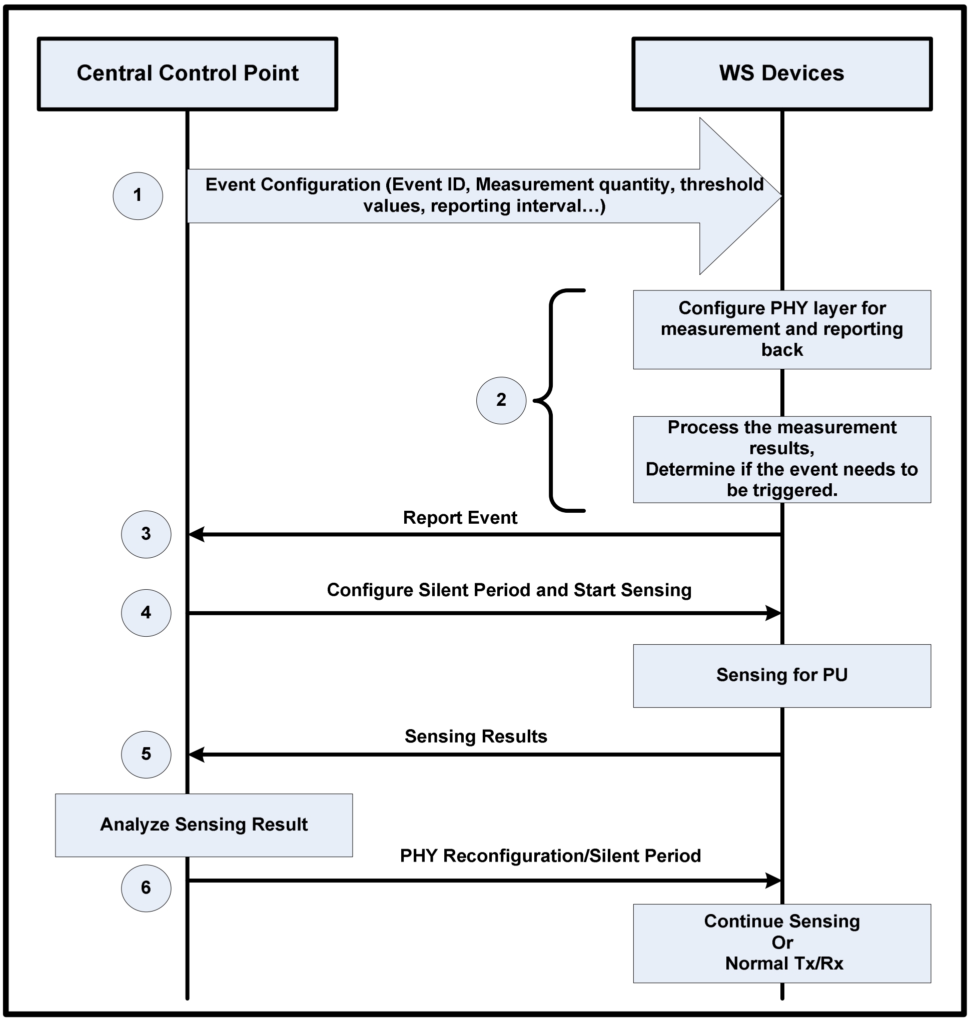


Figure 4: Information flow for Event Driven Sensing

Step 1: The CCP configures the WS device by sending an Event Configuration. The configuration information includes the Even ID, Measurement quantity, threshold values, measurement reporting interval, etc.

Step 2: The WS device configures its PHY layer to measure the quantities listed in the configuration information. These measurements can typically be done in parallel with normal TX/RX operations, and therefore do not affect the efficiency of the system. The PHY layer starts measurements and reports these to the higher layers in WS device. The measurement results are processed and compared with the threshold values set via the event configuration sent by the CCP. If the measurement results exceed a certain threshold value, an event is triggered.

Step 3: When an event is triggered at the WS device, the WS device reports this event to the CCP.

Step 4: The CCP analyzes information associated with the event to determine if sensing is required. If required, an asynchronous silent period at a specific time and for a specific duration is configured for the WS device and potentially other devices that need to perform sensing in the area. The configured silent period, information about actions after sensing and an indication to start sensing are sent to the WS device.

Step 5: The WS device(s) performs sensing and sends the sensing result to the CCP.

Step6: The CCP analyses the sensing result to determine the presence of a primary user (e.g. DTT). Based on the outcome of the analysis, the CCP may decide to reconfigure one or more WS devices to have them operate on another WS channel, continue the previously interrupted TX/RX operation, or continue sensing in order to further refine the sensing results for determination of the presence of a primary user. The decision is sent to the WS device as a control message.

4.1.3.1 Example Measurement for Event Triggering

The measurements used to trigger the event which starts sensing can typically be measurements that already exist in the current RAT of the system and which devices may utilize currently for other purposes. These measurements should give some indication of the potential arrival of an incumbent on the channel, and could be modified or tailored in order to fit such a need. Regardless of the type of measurement used for event driven sensing, the performance of this technique will depend on the transmit power of the incumbent system. In other words, for a scenario in which the incumbent uses a high transmit power, or is in close proximity with one or more WSDs, the measurement will be more likely to easily trigger the event at the arrival of the incumbent.

One example of a measurement that may be used by the WSDs to trigger an event for sensing is the measurement of channel quality at the PHY layer.

EXAMPLE: LTE makes regular channel quality measurements (CQI) and such measurements could also be used in order to determine when sensing should be performed.

The event configuration message indicating to the WS devices to measure and monitor CQI is sent to each WS node involved in event monitoring. The PHY layer of all WS devices in an active link connection that have received the event configuration message will periodically collect channel quality measurements. The measurement results are further processed and/or filtered based on event configuration sent by the CCP. Filtering is performed in order to avoid frequent event triggering and unnecessary sensing periods. This can be achieved by the introduction of a Time-To-Trigger (TTT), in which the measured channel quality is below a certain value for a minimum amount of time (the TTT) in order for the event to be triggered by the WS device. Each WS device will maintain the average CQI (CQI_{AVG}) measured on a particular link over a time span W in the recent past, and the instantaneous CQI (CQI_{INST}) measured over a time span of M. If the drop in CQI (CQI_{AVG} - CQI_{INST}) remains larger than some threshold D for a particular time to trigger (TTT), the WS device will generate an event A. This is illustrated in figure 5, which shows the filtering of CQI measurements (by higher layers) received from the PHY layer.

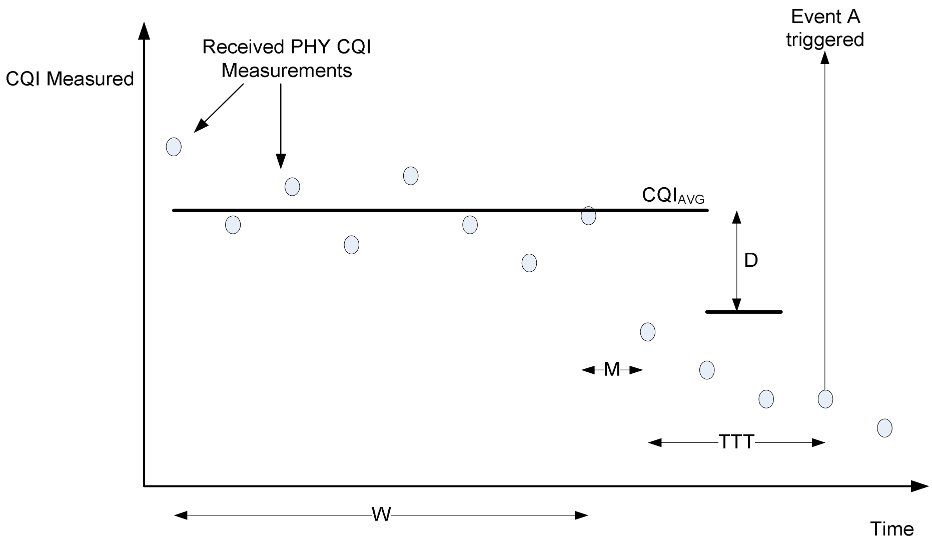


Figure 5: Triggering of an Asynchronous Sensing Event from CQI Measurements by a WS Node

With reference to figure 5, the values of D, M, TTT, and W can be entirely dictated by the CCP through the Event configuration message. In addition, the CCP could change these values based on probability requirements for detecting the incumbents (e.g. probability of false alarm), and which can be easily monitored using past statistical results.

Other examples for measurements used in event triggering are also possible. For example, in a Wi-Fi system, packet error rate, packet loss rate, retransmissions, or CSMA channel access time. For LTE, in addition to CQI, also direct measurements of the channel estimates or RSRP/RSRQ are also possible.

4.1.3.2 Silent period start time

The silent period configuration is determined by the CCP after it receives an event from one of the WSDs (see step 4 in the sequence chart). Due to the need for the CCP to send a silent period configuration message following this event, the start of the silent period will occur after the following delays:

1) The propagation delay (t_1) to the furthest node in the management area of the CCP, which can be determined through messaging on the downlink and uplink control channels.

2) The required delay (t_2) for a WS device to become quiet, which may include the delay required to clear PHY buffers.

3) The quieting period (t_3) for a data transmission that may have been sent by a WS device just prior to receiving the silent period message.

As a result, the start of the silent time will be scheduled at least $t_1 + t_2 + t_3$ after the sending of the silent period message. In addition to this information, the silent period message will contain a field which indicates the behaviour that the WS devices are to take immediately after they send their sensing results. Two possible behaviours can be expected: the WS nodes can be asked to continue sensing in order to further refine the results sent to the CCP (in which case the silent period will be implicitly extended until the next message is received) or the WS node can be asked to continue the previously interrupted TX/RX operation until the CCP commands another silent period, or reconfigures any WS nodes to a different frequency based on the sensing results (in step 6).

4.1.4 Coordinated Silencing

Detection of incumbents is possible through basic energy detection or feature detection techniques. The advantage of energy detection is its simplicity, which makes it attractive for use in cases where sensing is done at the WSDs (or mobiles) themselves. However, this type of sensing does not allow distinguishing between the incumbent and the transmission of the WSD itself. In addition, for reasons of cost, a WSD may contain only one receiver, and will therefore not be able to perform sensing with regular RX simultaneously. For these reasons, a coordinated time period where sensing is performed when part or all of the network has been silenced allows for a greater amount of flexibility in device design and location of sensing engines.

In-band sensing is significantly simplified by the use of coordinated silencing. Several studies in the area of cognitive radio have shown it advantageous to support the concept of silent (quiet) periods where the complete wireless system remains silent synchronously and periodically to be able to sense other users trying to occupy the same spectrum. These users can be primary users (in the case of incumbent protection), but may also be secondary users in order to support coexistence. With the use of a silent (quiet) period, the sensing algorithm does not need to distinguish between self network interference and primary/secondary user transmission.

The concept of a silent period or silent gap is shown in figure 6. Periods of active communication between devices in the network are interspaced with silent periods whereby the network in question is silenced and sensing of the primary user can be performed.

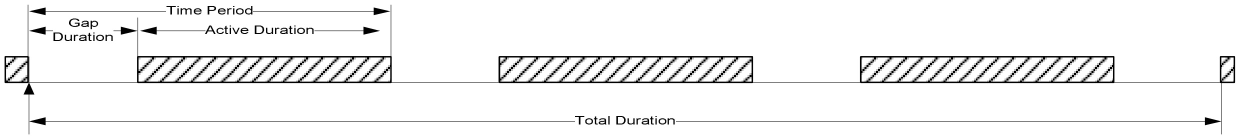


Figure 6: Illustration of a Silent Period or Silent Gap

Silent periods for in-band measurements have been considered in cognitive standards such as IEEE 802.22 [i.4], where a periodic quiet period is built into the frame structure. This concept can be further extended to provide greater flexibility in the scheduling of silent periods (by considering, for example the concept of an asynchronously scheduled silent period) and for consideration of existing technologies such as IEEE 802.11 [i.29] or LTE which may be adapted to operate in the TVWS spectrum.

Although techniques are currently available to perform sensing without the need of a silent period, the concept of a silent period is advantageous for reasons of sensing implementation, simplicity and accuracy. Firstly, a WSD will not need to distinguish between self-network interface and primary user (for incumbent detection) or secondary user (for coexistence) transmissions. For reasons of cost, a WSD may contain only one receiver front end, and will therefore not be able to perform sensing with regular RX simultaneously. Finally, a silent period can be easily built into the PHY and MAC layers of many existing RATs. For instance, the idea of creating measurement gaps (silent periods for sensing), performing measurements and reporting measurements back to the network has always been a part of the cellular system but only in the context of cell selection, mobility management and inter-RAT cell handover. The same framework can be leveraged to support white space communication in cellular systems by introducing sensing and silent period handling. For these reasons, a coordinated time period where sensing is performed when part or all of the network has been silenced allows for a greater amount of flexibility in device design and location of sensing engines.

4.1.4.1 Silencing in an LTE-Based System

An eNB/HeNB with several UEs within the cell is considered as shown in figure 7. The eNB/HeNB is capable of supporting primary, secondary (licensed) and supplementary (TVWS) cell communication. A supplementary cell refers to a cell operating in TVWS. It is expected that such a cell will have differences compared to a primary/secondary cell in order to support coexistence in TVWS as well as to mitigate interference that is not present on the licensed band. In other words, the eNB/HeNB and UE can communicate with each other over licensed band only, or, over both licensed and TVWS simultaneously.

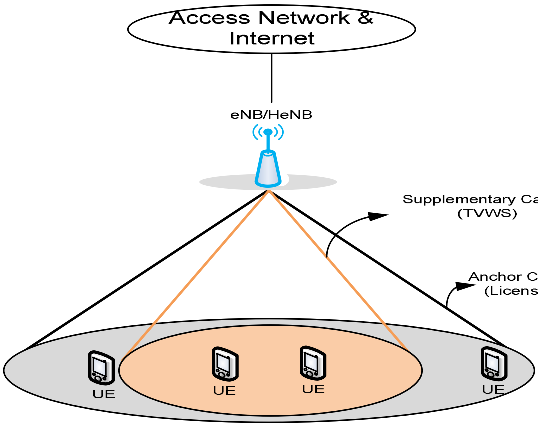


Figure 7: LTE System in TVWS

Sensing can be performed at the eNB/HeNB only or at both the eNB/HeNB and the UEs. The latter case is required in certain scenarios where interference from other primary/secondary systems are localized, and may also be required by certain regulators such as the FCC [i.1]. Sensing in the TVWS spectrum can achieve two purposes. The first one is to assess the channel quality between the UEs and the eNB/HeNB, and the other is to sense the presence of any primary user or interference from secondary users in the TVWS. The measurements (channel quality and sensing metrics) made on the License Exempt bands are reported to the eNB/HeNB periodically on the licensed uplink channels on the anchor cell.

The generic protocol stack at the UE, eNB/HeNB and MME and the logical communication link between corresponding modules in the protocol stacks at the nodes is shown in figure 7. The spectrum sensing functionality within the RRM can be split into 2 main modules. The sensing toolbox is the advanced signal processing module which implements the various detection and estimation algorithms to investigate the spectral/waveform characteristics to determine occupancy patterns within the spectrum by primary users, secondary users or interference in the spectrum. The sensing co-processor is the entity which schedules sensing operations on specific spectral bands at specific times for specific durations. It also interacts with the RRC module to signal sensing start times and gap schedules from eNB/HeNB to UE and also carry sensing results from UE back to eNB/HeNB. The sensing processor need not be present in the UE when sensing is performed at the eNB/HeNB only.

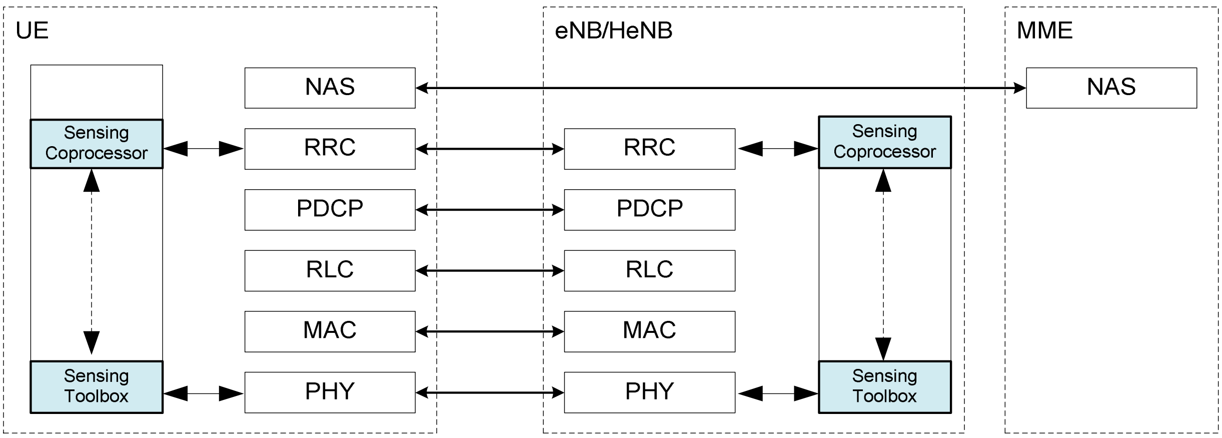


Figure 8: Control-plane Protocol Stack

4.1.4.1.1 Gap Definition through Clustering

The periodic/aperiodic silent gaps in general can be configured for all UEs in the system simultaneously or can be configured for clusters of UEs at a time by enabling spatial segregation of UE groups/clusters. There are two ways of achieving spatial segregation of UE clusters. One way is to use transmit beam forming where the transmitter in this mode is expected to support multiple transmit antennas for RF beam forming by pointing the main lobe towards a specific geographic area. Though RF beam forming could give rise to the side lobes which are not desirable, techniques such as non-uniform aperture function/amplitude shading could be used at the transmit antennas array to suppress the side lobes significantly. Another way is to use sectoral antennas to enable spatial separation of UE clusters.

EXAMPLE: A hexagonal cell could be divided into 6 sectors enabled by 6 sectoral antennas where each sector is 60° wide.

The following clause describes the three spatio-temporal approaches to silent period scheduling:

- **Broadcast-GAP Approach:** in this approach, silent period gaps occur temporally in a periodic/aperiodic fashion. The silent period schedule is common to all UEs in the supplementary cell i.e. all UEs in the supplementary cell are silent simultaneously during the course of active communication between eNB/HeNB and UE. This approach can be used for a short range cell (HeNB) or a macro cell. To enable the B-GAP approach, the supplementary cell could be configured to operate either in simplex mode (i.e. uplink only, or downlink only) or duplex mode (i.e. sequentially uplink and downlink transmission like TDD or single-frequency half-duplex FDD). In the case of duplex mode, the gaps could be scheduled to occur during transmission of downlink sub frames, or uplink sub frames, or both.

- **Multicast-GAP Approach:** in this approach, the UEs in a supplementary cell are divided into clusters. At any time instant, each cluster is either actively communicating with the eNB or is silent and sensing the LE spectrum for primary or secondary user. The schedule for sequential active and silent modes for each cluster is controlled by the eNB using spatial domain scheduling. This approach is restricted for use in a macro-cell deployment, due to interference which would hinder operation for a HeNB-type cell. This approach is intended for operation in downlink only mode especially for TVWS operation to achieve spatial segregation of UE clusters within a geographic coverage area of the supplementary cell. The supplementary cell could be configured to operate either in simplex mode (i.e. downlink only) or duplex mode (i.e. sequentially uplink and downlink transmission like TDD or single-frequency half-duplex FDD). In the case of duplex mode, the gaps are scheduled to occur during transmission of downlink sub frames only.

- **Hybrid-GAP Approach:** This approach is a combination of the above two approaches i.e. either all UEs in the supplementary cell are active or silent simultaneously, or, clusters of UEs are sequentially active or silent at a time. In this approach, the direction of operation of the supplementary cell and the occurrence of the B-GAP or M-GAP in a particular direction of transmission (uplink or downlink) are as stated in their corresponding descriptions.

Broadcast-GAP (B-GAP) Approach

To schedule a measurement gap for sensing, the eNB/HeNB, operating in a single LE spectrum band, can simultaneously silence all UEs in the supplementary cell to enable the UEs (and eNB/HeNB's own sensing toolbox) to make sensing measurements on the spectrum and report back to the eNB/HeNB (This does not preclude the case where only the eNB/HeNB performs sensing and measures the channel quality). To enable the above mentioned sensing in a cell over a spectrum a broadcast GAP (B-GAP) is introduced. Figure 9 depicts an example of Broadcast-GAP approach with all UEs simultaneously quiet periodically. To enable this, the eNB/HeNB should either incorporate a new measurement gap scheduler module or enhance existing scheduling algorithms to enable broadcast GAP scheduling and handling. Figure 10 depicts all UEs simultaneously active or simultaneously quiet (B-GAP) in a supplementary cell.

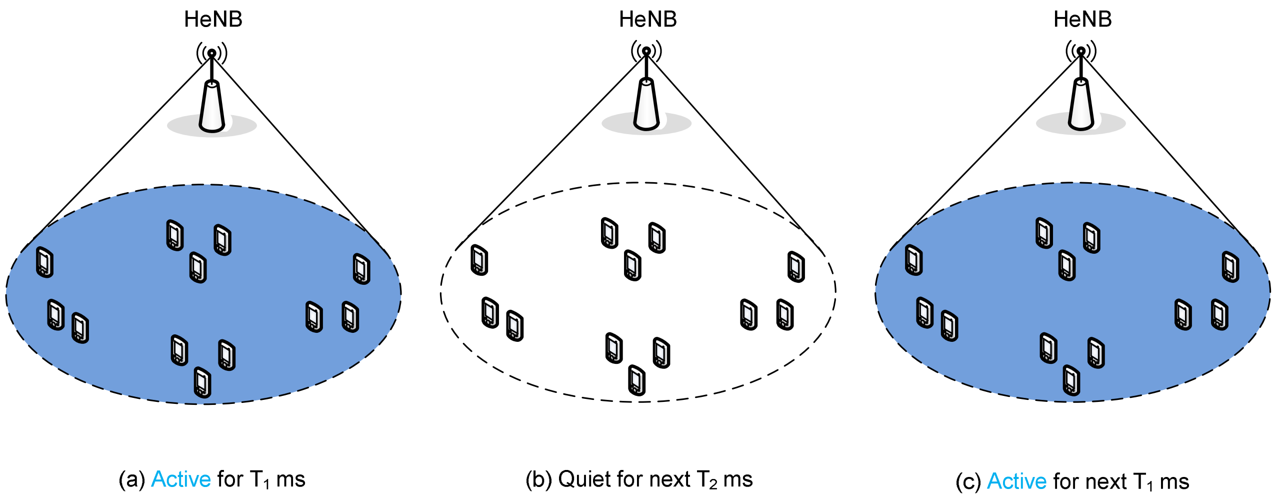


Figure 9: Broadcast-GAP with All UEs Simultaneously Quiet Periodically in Supplementary Cell

Figure 10: All UEs Simultaneously Active or Simultaneously Quiet (B-GAP) in a Supplementary Cell

Multicast-GAP (M-GAP) Approach

The main idea here is to schedule measurement gaps in the "spatial domain" i.e. the UEs in the cell are identified as being part of clusters as shown in figure 11. The eNB is assumed to have multiple antenna capability and can use transmit beam forming or sectoral antennas or directional antennas to serve each UE cluster independently in the downlink over the Supplementary Cell. The time schedule of serving each cluster with periodically scheduled gaps for sensing and measurements could be specific to each UE. Some of the advantages of M-GAP are as follows:

- Perform distributed sensing thus sharing the load of sensing across UEs.
- Generate a geographical distribution of interference pattern across supplementary cell.

- Useful from a power savings standpoint i.e. silence different clusters of UEs periodically/aperiodically to perform sensing operation only while scheduling a DRX for the rest of the receive path.

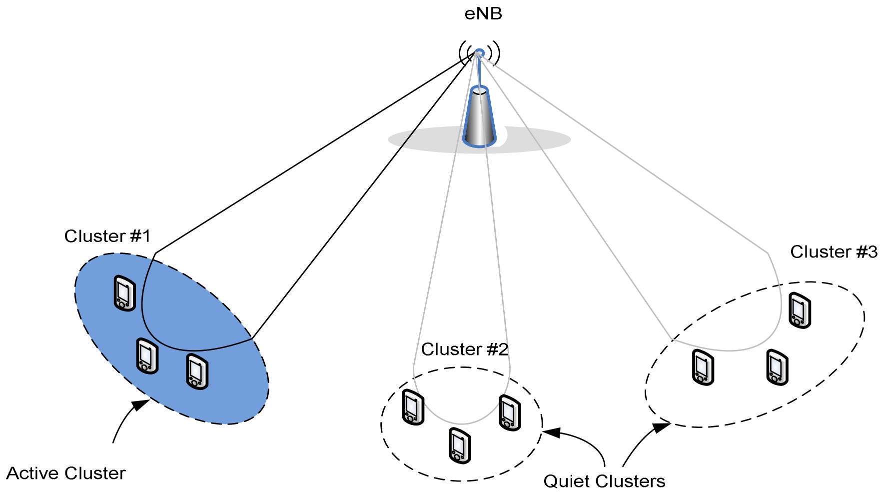


Figure 11: Cluster #2 and #3 are in M-GAP while Cluster #1 is Active

The M-GAP approach poses certain difficulties and challenges associated with the use of beam forming and sectoral antennas. These challenges are associated with the leakage of signal into the silent cluster:

- In beam forming, side lobe suppression may have limitations. A device which is in a silent cluster and close to the eNB may receive energy from side lobes that would limit its ability to perform sensing.
- With sectoral antennas, UEs located in sector overlap would experience the same problem.

There are three approaches that can be adopted:

- Sequentially Quiet Clusters: each cluster is silenced sequentially while all others are active.
- Sequentially Active Clusters: each cluster is active while all others are silenced.
- Subset Active Clusters: a hybrid approach where a subset of all UE clusters is active at a given time and all others are silent.

The case of sequentially active clusters is shown in figure 12, and can be generalized for the other cases.

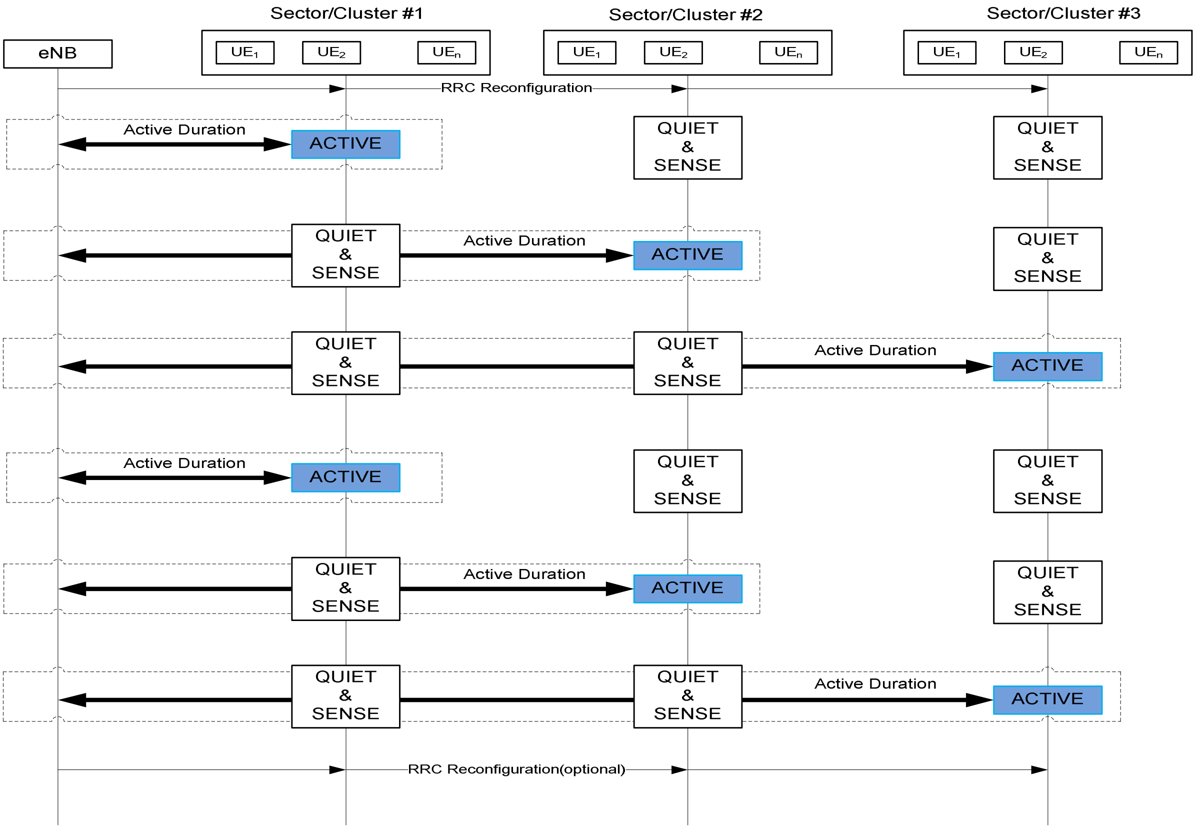


Figure 12: Logical Enable Sequentially Active Clusters

Hybrid-GAP (H-GAP) Approach

This approach is a hybrid of the B-GAP and M-GAP approach as the name suggests. As shown in figure 13, the UEs in the Supplementary Cell can be simultaneously active for a period of time(say, T1 ms), followed by only a cluster #3 being quiet while all other clusters are active for, say, T2 ms, followed by only a cluster #2 being quiet while all other clusters are active for, say, T2 ms, followed by only a cluster #1 being quiet while all other clusters are active for, say, T2 ms, followed by all UEs being quiet for, say, T3 ms. This sequence can continue periodically/aperiodically for the total required duration of sensing. The sequence with which B-GAP and M-GAP are scheduled can be chosen in any fashion by the eNB/HeNB.

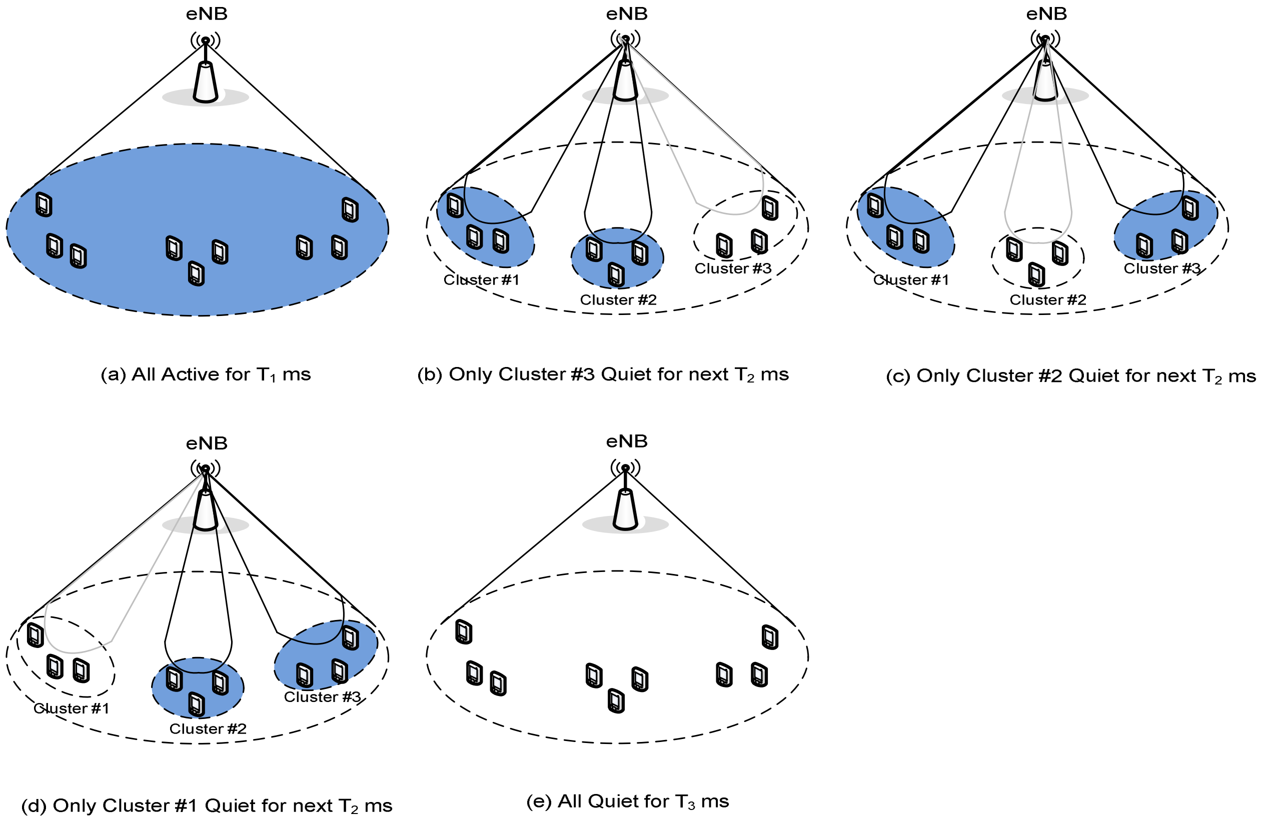


Figure 13: Hybrid-GAP

4.1.4.1.2 Silencing through the Absence of Scheduling

In certain cases, for example when UEs do no not support sensing capability, sensing may be performed only at the eNB/HeNB. In this case, the eNB/HeNB is free to perform sensing at its own times (e.g. periodically or at strategic times dictated by the scheduler's load). The eNB/HeNB can establish a silent period for sensing through the absence of scheduling of uplink grants or downlink allocation to the UEs on the supplementary cell. While allocations and grants are still made on the licensed carriers, the eNB/HeNB will not schedule any uplink grants or downlink allocations for data transfer on the supplementary cell. This technique can be applied for both supplementary cells operating in simplex mode (uplink only or downlink only mode), as well as for a duplex mode (e.g. TDD or single-frequency Half-Duplex FDD).

For example, for operation in a supplementary cell operating in the uplink direction and during the silent period, the eNB/HeNB can perform sensing on the TVWS bands used by the supplementary cells on all symbols in a subframe that are not used by the UE for transmission of SRS. The HeNB can therefore use two approaches for scheduling the sensing by its own Sensing Toolbox:

- The HeNB can perform sensing on all subframes which do not contain SRS from any UEs, as well as on SRS subframes as long as the sensing operation is interrupted during the last OFDM symbol of the subframe (where the SRS resides). This scheme would be beneficial for short sensing bursts which need to be done occasionally by the HeNB.
- The HeNB can temporarily disable (through RRC signaling) SRS on the supplementary carrier so that sensing can be performed without interruption by the HeNB over longer periods of time. This approach would be preferred in the case the sensing toolbox requires a long period of sensing time which spans over several frames.

4.1.4.1.3 A Quiet Period Scheme for LTE-TDD

For LTE-TDD system as a single CRS (i.e. there are no CRSs using other transmission techniques), the guard period (GP) existing in LTE-TDD radio frame [i.12] (in figure 14) provides one approach to achieve quiet periods. Sensing operation in this clause is considered to be transparent of the LTE-TDD system operation. Thus, it is assumed that the existing GP can be used for sensing.

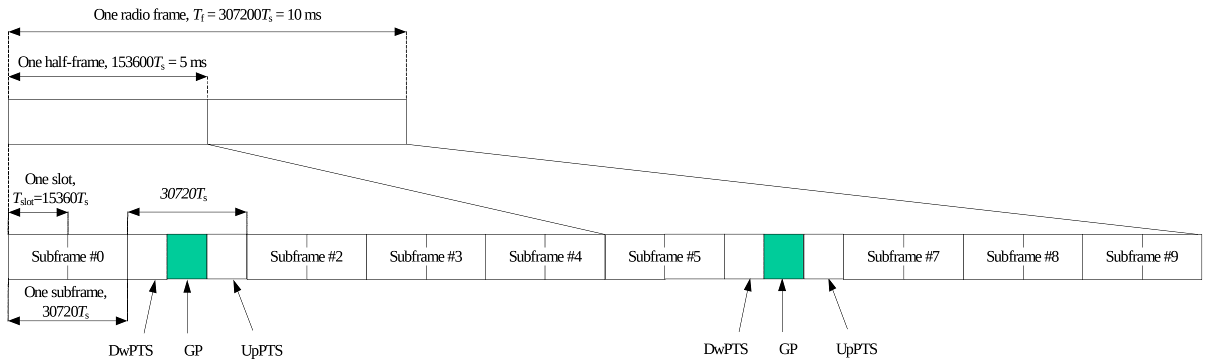


Figure 14: Radio frame structure for LTE-TDD

A GP is required in for downlink-to-uplink switch. Table 1 gives the supported configurations in LTE-TDD system where the length of each field is given in multiple of OFDM symbols. The length of GP could be flexibly configured to efficiently support different cell sizes up to 100 km, as well as to handle BS to BS interference due to propagation delay.

Table 1: GP length (# of OFDM symbols)

Format	Normal CP			Extended CP		
	DwPTS	*GP*	*UpPTS*	*DwPTS*	*GP*	*UpPTS*
0	3	10		3	8	1
1	9	4		8	3	
2	10	3	1	9	2	
3	11	2		10	1	
4	12	1		3	7	2
5	3	9		8	2	
6	9	3	2	9	1	
7	10	2		-	-	-
8	11	1		-	-	-

Since eNB has a greater antenna height (above terrain) than the UE, it may have a higher sensitivity to incumbent user signals due to a higher probability of being in line-of-sight of the incumbent. Therefore during a GP, only the eNB will perform the in-band sensing task. However there may still be some residual signals from adjacent eNBs due to signal propagation delay. This may affect the sensing performance at eNB.

The main advantages of the GP as QP are the following:

1) Protocol compatibility:

   - In GP, each eNB stops all transmissions and receptions. Therefore, the spectrum sensing module located in eNB could implement sensing without affecting any LTE-TDD data transmission, and have no impact on existing LTE-TDD protocol design, which is rather important for standardization considering the backward compatibility.

2) Flexibility:

   - The length of GP could be configured flexibly for the adopted spectrum sensing algorithms.

The quiet period scheme for LTE-TDD is now described in more detail.

In LTE-TDD system, eNB stops transmission in GP in order to prevent the interference between downlink and uplink transmissions. GP is an inherent quiet period in LTE-TDD system. However, in GP, spectrum sensing may still be interfered by LTE signals, which is caused by the neighbouring eNB transmissions and the uplink transmissions. In order to avoid such interference, some Guard Duration (GD), including a Pre-GD and a Post-GD, should be reserved in a GP. As shown in figure 15, the positions of Pre-GD and Post-GD are determined by the following configurations:

1) $T_{Pre\text{-}GD}$, the length of Pre-GD. A Pre-GD should be set after the DwPTS, in order to avoid the interference from adjacent cells. And the length of Pre-GD should be larger than *d/c*, where *d* is the maximum distance between the operating eNB and the potential interference eNBs, and *c* is the velocity of electromagnetic waves. In order to reduce the requiredto Pre-GD length, the inter-cell interference, especially the interference among distant cells, should be controlled strictly by network planning or ICIC technologies. For a practical example, if the distance between two eNBs is 1 000 m then the propagation delay from one site to another one is about 3,3 us, which is much less than the ~700 us GP.

2) $T_{Post\text{-}GD}$, the Length of Post-GD. Post-GD is located at the end of GP. The purpose of Post-GD is to avoid the interference from the UL transmission, which may be caused by the TA (timing advance) errors. Therefore, Post-GD should be longer enough to prevent the possible interference from UL transmission, i.e. it should be larger than the maximum possible TA errors.

Then, the quiet period could be set between the end of the Pre-GD and start of the Post-GD based on the above configurations. eNB and/or UE should perform spectrum sensing within the quiet period.

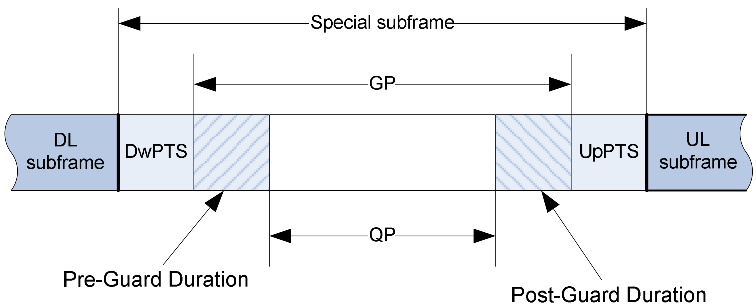


Figure 15: Quiet period in the special sub-frame

Assuming T_{GP} is the length of GP, the length of quiet period is T_{GP}-$T_{Pre\text{-}GD}$ -$T_{Post\text{-}GD}$. Traditionally, the length of GP mainly depends on the cell size, i.e. the larger the cell is, the longer GP it requires. However, short GP will cause degradation of sensing performance. Therefore, it is recommended to use a relative long GP configuration to guarantee the sensing performance, even though the cell size is small.

Note that using GP for sensing may be unfeasible in large cells, because in large cells the maximum configurable GP is used to avoid interference between UL and DL at eNB. However, in TVWS the cell size is not expected to be large, and so in this case, the GP provides a practical method for the quiet period.

4.1.4.1.3.1 Multi-Slot Sensing

Spectrum sensing requires detection of very weak signals with high detection probability, which demands a long time for sensing. However, the GP-based QP could only provide less than ~700 µs for spectrum sensing, which may be not enough for the weak signals. Multi-slot sensing, shown in figure 16, is an effective way to improve the sensing performance for such short QPs. Compared with single QP sensing, more samples could be obtained by combining a number of QPs, therefore the sensing performance could be improved. In LTE-TDD system, GP appears with a relative high frequency (5 ms or 10 ms period), therefore it is very easy to get many QPs to improve the sensing performance.

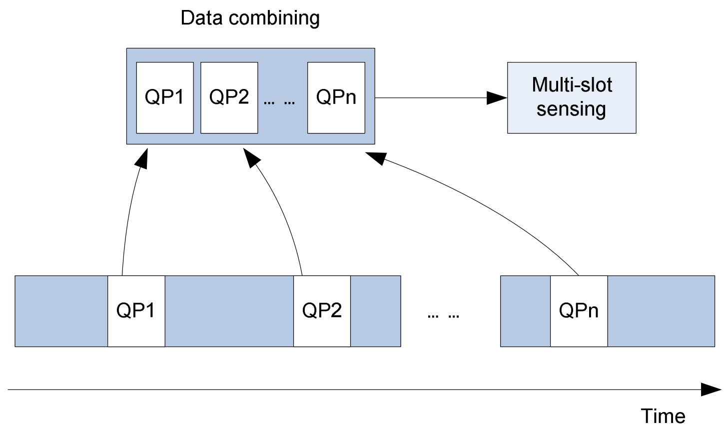


Figure 16: Multi-slot sensing

4.1.4.1.3.2 Simulation Results for an LTE TDD System

An LTE TDD system with 20 MHz bandwidth operating in the TVWS band, and an inter-site distance of 10 km are here assumed.

The length of Pre-GD, Post-GD and quiet period could be calculated as follows:

Length of Pre-GD

Assuming the interference mainly comes from the surrounding cells within three layers, as figure 17 illustrates, the maximum distance between two mutually interfering eNBs is 30 km. Cell 0 will perform the sensing. Therefore the length of Pre-GI should be larger than: 30 km/c = 100 µs, where c is the velocity of light, i.e. 3×10^8 m/s. In practice, the maximum distance of mutually interfering eNBs may be different depending on the cell radius. However same method could be used to calculate the length of Pre-GD.

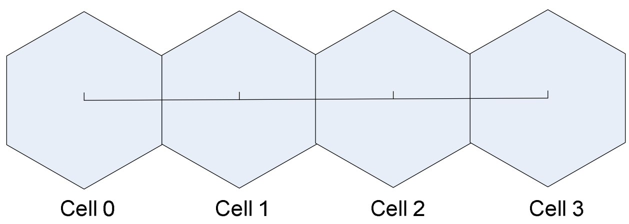


Figure 17: Distance between mutually interferingco-interference cells

Length of Post-GD

For OFDM/SCFDM, cyclic prefix (CP) is inserted at the beginning of the symbol. The uplink signal should not arrive at eNB earlier than the length of CP, otherwise the signal may not be received correctly. Therefore the length of Post-GD could be configured as a value larger than the length of CP of the first symbol in UpPTS. Specifically, if UpPTS has one OFDM symbol, sounding reference signal (SRS) will be transmitted in UpPTS and the CP of SRS is 144 samples, then the Post-GD could be larger than 144*1/(15 000*2 048) = 4,7 µs. If UpPTS has two OFDM symbols, then the first OFDM symbol is random access preamble. The CP of random access preamble is 448 Ts, therefore the Post-GD could be larger than 448*1/(15 000*2 048) = 14,6 µs.

Length of quiet period

If UpPTS has one symbol, then the longest GP is 714 µs, therefore the length of quiet period should be less than 714 - 4,7 - 100 = 609,3 µs. If UpPTS has two symbols, the longest GP is 643 µs, then the corresponding quiet period should be less than 643 - 14,6 - 100 = 528,4 µs. In the simulation, four quiet period lengths are evaluated, including 500 µs, 400 µs, 300 µs and 200 µs.

In the simulation, a 20 path Rician fading channel with 10 dB K-factor, which is defined in DVB-T specification for fixed outdoor reception, is used as the channel model between TV station and the LTE eNB. Two kinds of TV systems (DTMB for single carrier signal and DVB-T for multi-carrier signal) are considered in the simulation.

Simulation results for DTMB

Two sensing algorithms are evaluated for DTMB, i.e. the cross correlation detection and the Maximum Eigenvalue to Trace (MET) detection [i.19].

The cross correlation detection is a popular signal feature detection algorithms. It exploits the correlation between the received signal and the known frame header signal. Let $r_m(n)$, $0 \le n \le N$ be the received signal in the m^{th} GP, and $s(n)$, $0 \le n \le L-1$ be the frame header signal. Then the cross correlation between the received signal and the frame header signal in m^{th} GP is:

$$T_m = \max_k \left(\sum_{n=0}^{L-1} r(n+k)s(n) \right), 0 \le k \le N-L-1 \quad (1)$$

As described above, a multi-slot sensing scheme is used to improve the sensing performance. Firstly, M correlation values are obtained in 'M' GPs using the above algorithm, and then the M values are summed up and compared with a threshold Γ, i.e.:

$$T = \sum_{m=1}^{M} T_m \gtrless \Gamma \quad (2)$$

It should be noted that, for cross correlation detection, a very short QP may result in the frame header being received imperfectly in some of the QPs. However, the multi-slot sensing scheme resolves this problem well. Even if the frame header is not received in part of QPs, the sensing performance could still be acceptable by the contribution of QPs in which the frame header is received.

Different from cross correlation algorithm, the MET algorithm is a blind sensing technique which does not need the knowledge of the signal and could be used for any type of primary systems. This algorithm utilizes the correlation between the signals received by different antennas of eNB. Assuming eNB has two receiving antennas, the covariance matrix of the received signal is calculated as:

$$R_m = \frac{1}{N} \sum_{n=0}^{N} r(n) r(n)^{\mathrm{H}} \quad (3)$$

where $r(n) = [r_1(n) \quad r_2(n)]^T$ is the received signal of two antennas. Then a SVD decomposition is performed for R_m, and the maximum eigenvalue γ_m of R_m is obtained. Then the test statistic of m^{th} GP is the ratio between γ_m and the trace of R_m, i.e.:

$$T_m = \frac{\gamma_m}{\mathrm{trace}(R_m)} \quad (4)$$

Similar to the multi-slot cross correlation algorithm, the test statistics obtained in M GPs is then summed up and compared with a threshold.

In the simulation, a detection threshold of -114 dBm for DTV is adopted to evaluate the sensing performance, which is the requirement of spectrum sensing by FCC. Furthermore, 99 % is adopted as the requirement for detection probability. Assuming the Power Spectrum Density (PSD) of noise is -174 dBm/Hz, and the noise figure of eNB is 5 dB. Then the detection threshold in SNR form could be calculated as: -114 - (-174 + 5 + 10log^8 × 10^6) = -14 dB. That means the DTMB signal with SNR more than -14 dB can be detected with detection probability above 99 %.

Figures 18 and 19 show the simulation results of the two algorithms, where cross correlation utilizes 50 GPs and MET utilizes 100 GPs, other detailed simulation configurations are listed in table 2. The results show that, for all the cases, the sensing performances exceed the requirement of detection threshold (i.e. -14 dB) and detection probability (i.e. 99 %). Specifically, for cross correlation detection, by combining 50 GPs, -20 dB signal could be detected with 100 % detection probability, even when the QP length is only 200 µs. And for MET detection, -17 dB signal could be detected with 100 % detection probability with a 200 µs QP length and 100 GPs combination.

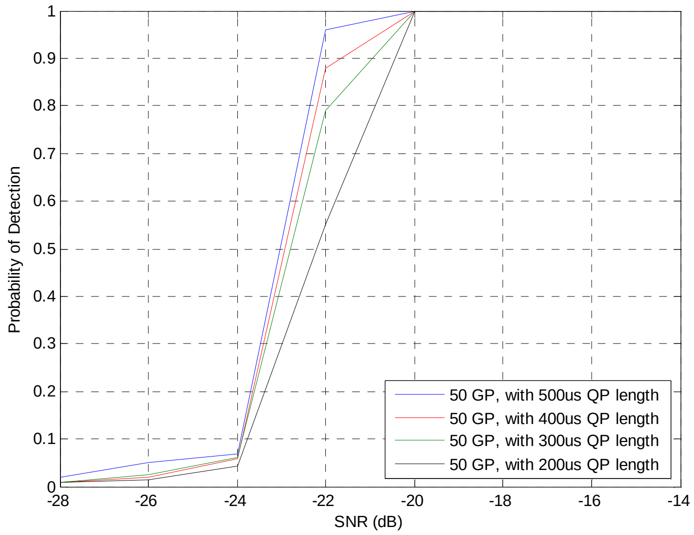


Figure 18: Simulation result of cross correlation detection of DTMB signal

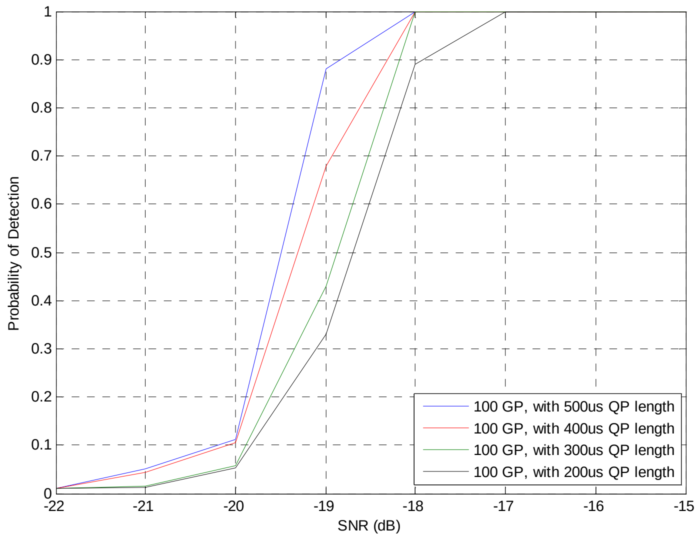


Figure 19: Simulation result of Maximum Eigenvalue to Trace (MET) detection of DTMB signal

Table 2: Simulation parameters

Category	Configuration
TV signal type	DTMB
Length of DTMB frame header	55,6 µs
Interval of DTMB frame	555,6 µs
Frame header	PN 420
Sensing algorithm	Cross Correlation MET
RX number	1 for cross correlation 2 for MET detection
False alarm probability	1 %
Detection probability	99 %
Detection threshold	-14 dB(SNR)
QP length	500 µs, 400 µs, 300 µs, 200 µs
QP interval	10 ms
Channel model	20 Paths Rician channel, 10 dB K factor (DVB-T fixed reception)

Simulation results for DVB-T

DVB-T is an OFDM based multi-carrier signal, and its frame structure is very different from DTMB signal. Therefore, the frame header based cross correlation algorithm cannot be utilized for DVB-T signal directly. However, for DVB-T signal, reference signals are inserted in the OFDM symbols for synchronization and channel estimation. The reference signals are generated from a Pseudo-Random Binary Sequence (PRBS) and have fixed value and pattern. For spectrum sensing, this signal feature could be exploited for cross correlation algorithm.

In DVB-T, pilot symbols are inserted into each OFDM symbol in frequency domain. However, since it is not possible to synchronize with DVB-T signal when perform spectrum sensing, the cross correlation in frequency domain is not feasible. Instead, using the IFFT transform of frequency domain pilot sequence, i.e. the time domain pilot signals, a time domain cross correlation algorithm could be designed.

In DVB-T, there are two kinds of reference signals [i.20]: continual pilot and scattered pilot. Let $P_c(i)$ denote the frequency domain continual pilot sequence in one OFDM symbol. Then $P_c(i)$ could be written as:

$$P_c(i) = \begin{cases} c(i), & i \in I_c \\ 0, & i \notin I_c \end{cases} \tag{5}$$

Where $c(i)$ is the pilot symbol generated by PRBS sequence, and I_c is the set of subcarrier indices for continual pilot. Similarly, the scattered pilot sequence $P_s(i)$ is:

$$P_s(i) = \begin{cases} c(i), & i \in I_s \\ 0, & i \notin I_s \end{cases} \tag{6}$$

where I_s is the set of subcarrier indices for scattered pilot.

Excepting the subcarrier indices included in I_c and I_s, other subcarriers are mapped with data symbols. Let $S(i)$ denote the data sequence, then:

$$S(i) = \begin{cases} a(i), & i \in I_{c,} \, i \notin I_s \\ 0, & others \end{cases} \tag{7}$$

where $a(i)$ is the data symbol in subcarrier *i*. Obviously, the entire form of one OFDM symbol in frequency domain should be:

$$d(i) = P_c(i) + P_s(i) + S(i) \tag{8}$$

After IFFT transform, the OFDM signal in time domain could be obtained:

$$x(\mathrm{n}) = \mathrm{F}^{-1}(d(i)) = \mathrm{F}^{-1}(P_c(i)) + \mathrm{F}^{-1}(P_s(i)) + \mathrm{F}^{-1}(S(i)) \tag{9}$$

where $\mathrm{F}^{-1}(\cdot)$ denotes the inverse Fourier transform. The time domain DVB-T signal could be divided into three parts, the:

- time domain continual pilot $\mathrm{F}^{-1}(P_c(i))$;
- time domain scattered pilot $\mathrm{F}^{-1}(P_s(i))$; and
- time domain data signal $\mathrm{F}^{-1}(S(i))$.

  Let $p(n) = \mathrm{F}^{-1}(P_c(i)) + \mathrm{F}^{-1}(P_s(i))$ and $s(n) = \mathrm{F}^{-1}(S(i))$ denote the pilot signal and data signal in the time domain respectively, then $x(n) = p(n) + s(n)$.

After inserting CP, the whole OFDM symbol in the time domain could be finally obtained. Assuming the number of OFDM subcarriers is *N* (including the unused subcarriers), the length of CP is *L*, then the time domain pilot signal $p(n)$ has a length of *N*+*L* samples.

A cross correlation algorithm could be designed based on the time domain pilot signal. Let $r(n)$ be the received signal. In each GP, assuming *K* samples are received, then *K* cross correlation results between $r(n)$ and $p(n)$ could be obtained by sliding the received signal sample by sample, and calculating the correlation value after sliding, i.e.:

$$\gamma(k) = \left|\sum_{n=0}^{N+L-1} r(n+k) * p(n)\right|, 0 \le k \le K-1 \tag{10}$$

where *k* is the number of sliding times. Since the length of $p(n)$ is *N*+*L*, the cross correlation result should be summed in the length of *N*+*L*, i.e. from 0 to *N*+*L*-1, and calculate the modulus.

If the received signal is DVB-T, $r(n)$ will contain the information of $p(n)$. The cross correlation will appear a peak for a certain value of *k*. Therefore, if a peak value of $\gamma(k)$ is detected, the received signal could be determined to be DVB-T signal.

For multi-slot sensing, assuming the peak value in m^{th} GP is:

$$T_m = \max_k \gamma_m(k), \forall k \in [0, K-1] \tag{11}$$

then *M* values obtained in *M* GPs could be summed up and compared with a threshold Γ, i.e.:

$$T = \sum_{m=1}^{M} T_m \gtrless \Gamma \tag{12}$$

Then the final decision could be made based on the comparison.

It should be noted that, within arbitrary four consecutive OFDM symbols, the scattered pilot patterns in each OFDM symbol are different, and such pattern repeats every four consecutive OFDM symbols. The above method only uses pilot signal in one OFDM symbol, which means only the continual pilot and part of scattered pilot are utilized for sensing. However, in order to enhance the performance, pilot signal of four consecutive OFDM symbols could be utilized for sensing at the cost of complexity increase. In the simulation, such extended pilot signal is adopted. Correspondingly, equation (10) should be modified as:

$$g(k) = \left|\sum_{n=0}^{4(N+L)-1} r(n+k) * p(n)\right|, 0 \le k \le K-1 \tag{13}$$

Another sensing algorithm MET has already been described in the DTMB part. MET is a blind sensing algorithm, which means it is available for all kinds of TV signal. The simulation result of MET algorithm for DVB-T signal is also provided here.

In ECC report 159 [i.3], the detection threshold for DVB-T signal in different scenarios are studied. And the detection thresholds in fixed WSD outdoor scenario are summarized in table 3. For this scenario, the sensing threshold varies between -89 dBm and -107 dBm for 8 MHz TV bandwidth. Comparing with the FCC threshold (i.e. -114 dBm for 6 MHz_TV bandwidth), these ECC thresholds are less stringent. If we adapt the FCC threshold to 8 MHz bandwidth, the threshold will be higher than -114 dBm, e.g. about 1,2 dB higher (i.e. -112,8 dBm) if we assume the two thresholds have same power spectrum density. In order to evaluate the sensing performance more strictly, the bandwidth difference is ignored and the FCC threshold (i.e. -14 dB in SNR form) is still used for DVB-T. Other simulation parameters are listed in table 4.

Figures 20 and 21 give the simulation results of cross correlation algorithm and MET algorithm for DVB-T respectively. Both the algorithms use 50 GPs for spectrum sensing, but with different QP lengths. It can be seen that both the algorithms achieve 100 % probability of detection when SNR > -14 dB, which means the FCC and ECC threshold are both reached.

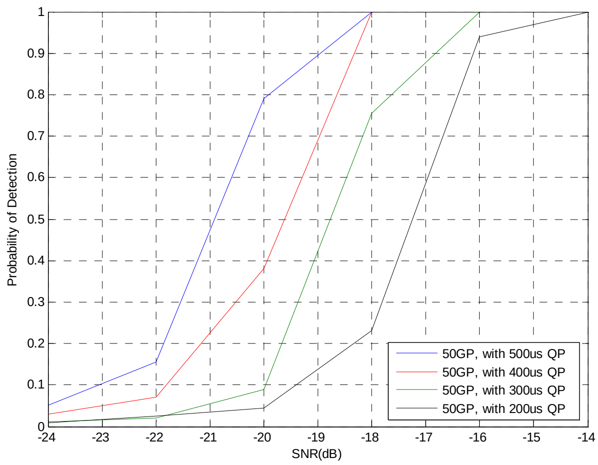


Figure 20: Sensing performance for cross correlation algorithm for DVB-T signal

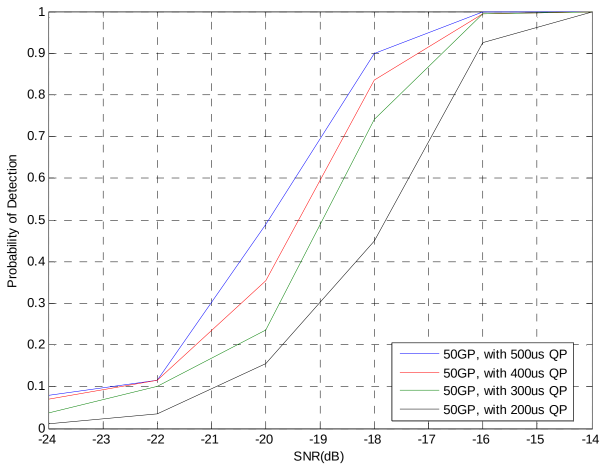


Figure 21: Sensing performance for MET algorithm for DVB-T signal

Table 3: Detection threshold for fixed WSD in different scenarios (from ECC report 159)

	WSD Outdoor
DTT outdoor	DTT Fixed @10 m 95 % - WSD Fixed @30 m: **-90,86 dBm**
	DTT Fixed @30 m 70 % - WSD Fixed @30 m: **-106,89 dBm**
	DTT Fixed @10 m 70 % - WSD Fixed @30 m: **-97,05 dBm**
	DTT Fixed @30 m 95 % - WSD Fixed @30 m: **-100,70 dBm**

Table 4: Simulation parameters

Category	Configuration
TV signal type	DVB-T
Duration of DVB-T symbol	2 048 samples, i.e. 224 µs
CP length	256 samples, i.e. 28 µs
Sensing algorithm	Cross Correlation MET
RX number	1 for cross correlation 2 for MET detection
False alarm probability	1 %
Detection probability	99 %
Detection threshold	-14 dB (SNR)
QP length	500 µs, 400 µsµs, 300 µs, 200 µs
QP interval	10 ms
Channel model	20 Paths Rician channel, 10 dB K factor (DVB-T fixed reception)

4.1.4.1.3.3 Conclusions

By reserving Pre-GD and the Post-GD, a quiet period could be set within the GP without interference from LTE-TDD UL/DL transmissions. Simulation results of DTMB and DVB-T of 2 k OFDM system show that, under the simulation assumptions (e.g. -174 dBm/Hz noise PSD, 5 dB noise figure, 0 dB antenna gain, and Rician channel with 10 dB K factor), spectrum sensing could achieve the FCC and ECC threshold for fixed outdoor WSD by a reasonable QP setting and an appropriate selected sensing algorithm. Furthermore, the GP based QP design does not require modification of LTE specifications.

4.1.4.2 Silencing in a WiFi-Based System

In WiFi networks such as 802.11 [i.29], transmissions between the AP and stations are synchronized through the use of a beacon frame transmitted by the AP in infrastructure mode. Silent measurement periods were already introduced in 802.11 [i.29] for detection of radar in the 5 GHz bands [i.5]. The coordination of these measurement is performed through the transmission of a quiet element in the beacon frame transmitted by the AP.

Throughput losses and adverse effects of latency resulting from the introduction of silent periods in a WiFi system can be mitigated by aggregating a WiFi system's bandwidth over multiple channels in the TVWS and having the silencing for the system performed in an independent and non-overlapping fashion.

The concept of aggregating multiple channels and using a primary channel was introduced in IEEE 802.11n [i.5] and IEEE 802.11ac [i.30]. This concept is well-tailored to the use of WiFi in TVWS, as TVWS channels will generally be limited in spectrum (e.g. the FCC has defined 6 MHz wide channels for the use of its TVWS), and could be unavailable or unusable at intermediate periods. In addition, a set of contiguous channels in the TVWS will likely be unavailable in most urban areas.

In order to schedule periodic silent periods over the set of aggregated channels and maintain channel throughput despite the presence of silent time, the silent periods are scheduled by the AP in a non-synchronized fashion when possible. This ensures that there is always at least one channel in order to ensure maintenance of the channel traffic on the aggregated channel link. It also ensures that the primary channel (which is tasked with the control of the CSMA operation as in IEEE 802.11ac [i.30]) is always available for use by the AP and their associated stations.

The basic concept is shown in figure 22 for a case with four channels and a channel acting as primary channel. The system then coordinates the change of the primary channel based on the silent period schedule. For example, the primary channel may be changed in a round-robin fashion and automatically with the occurrence of each silent period. Regardless of the length of the silent period, the system maintains a minimum throughput and low latency impact as a result of the silent period. An example is shown in figure 22.

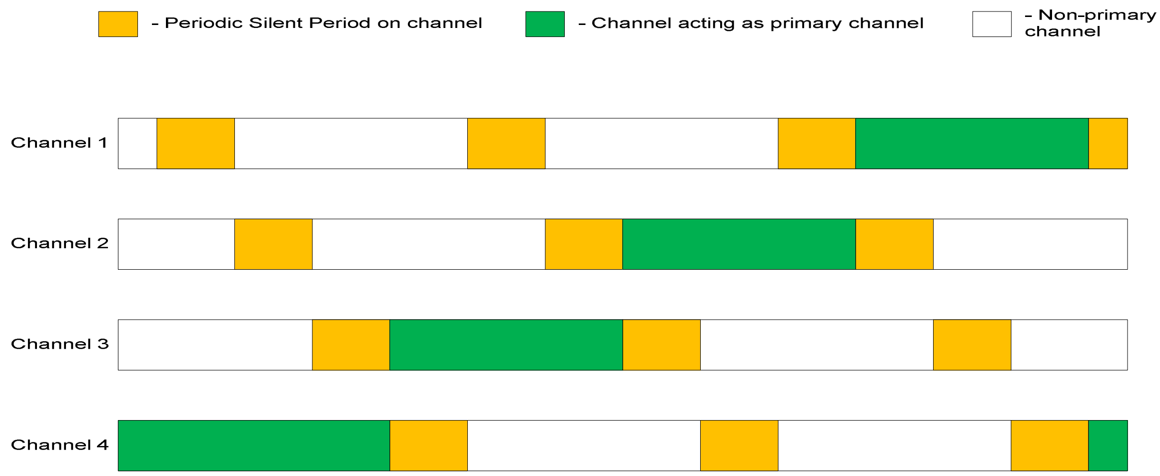


Figure 22: Use of Non-Synchronized Silent Period Schedule in a Multi-Channel System

Due to the dependence of synchronization and transmission patterns in WiFi on the beacon, the beacon is a likely candidate for sending information about the silent period schedule. The quiet element introduced in IEEE 802.11 [i.29] for 5 MHz operation is a good example. Extensions can be made to this quiet element for a WiFi-based cognitive radio system operating in TVWS in order to increase the flexibility of scheduling silent periods for sensing in the TVWS. For instance, silent periods can be scheduled to occur between beacons, as shown in case 3 of figure 23 (the quiet period element in IEEE 802.11 [i.29] supports only case 1 and 2). Inter-beacon silent periods simplify the task of scheduling silent periods across multiple channels in a round-robin fashion as shown in figure 23.

Figure 23: Use of the Beacon for Scheduling Silent Period Information

4.2 Advanced Geo-location Database Design

4.2.1 General

The use of geo-location database is preferred by regulatory bodies [i.1] and [i.3]. According to locations provided by CRSs and a geo-location database, CRSs can determine which frequencies they can use at their current locations. This method can provide a reliable protection to TV systems since the spectrum usage of TV systems is slowly varied.

4.2.2 Output Power Control Techniques to Address an Aggregated Interference Problem due to Simultaneous Transmission of Multiple WSDs defined in ECC REPORT 186 and its Feasibility Study Analysis

This clause introduces a feasibility study on output power control techniques of WSDs based on an aggregated interference margin (IM) setting defined in ECC Report 186 [i.23], clause 5.2.4, which it is shown as follows:

- Fixed/Predetermined IM value setting based on the potential maximum number of WSD interferers in each operational frequency in a given area at the same time.

- Flexible IM value setting based on the maximum number of active/actual WSD interferers, in a given area operating at the same time.
- Flexible minimized IM value setting based on the actual characteristics of each active WSD interferer in each operational frequency of WSD in a given area at the same time.

In the situation that active WSDs are master WSDs, the results in ECC Report 186 [i.23], annex 1, have shown that the consideration of the number of active master WSDs of each available channel in the *IM* calculation engine will bring us the highest communication opportunity of master WSDs, according to the performance differences among fixed, flexible and minimized *IM* calculation methods. Subsequently, the minimized *IM* calculation method can show the highest performance in three methods, because there will be some redundancy in calculating output power level of master WSDs in cases where the fixed and flexible margin based *IM* calculation methods are adopted. This may be due to the fact that the fixed and flexible margin based calculation methods cannot differentiate between the path loss conditions of a target master WSD from one of the other potential interferers in calculating output power level of a target master WSD. Table 5 shows the comparison of different calculation methods from viewpoints of the master WSD network capacity, the system overhead and the calculation overhead. One can see that the system overhead will increase due to the consideration of the number of active master WSDs in each available channel, because the number of interaction between the *IM* calculation engine and its connected master WSDs will be significantly increased due to the consideration of new-entry/deactivation of master WSD(s) in actual network operation. Subsequently, the calculation overhead in the calculation engine will be much higher than a case where fixed margin based calculation method is adopted. However, if the calculation engine has high computation capability through the use of multi-core processors configuration, there may be small impact in comparison with the impact on the increase of the system overhead via proposed method. Therefore, this clause just focuses on the system overhead issue.

This clause is organized as follows. First, the target scenario of this study and its system model and information flow among relevant entities are introduced. Next, some analysis on the system overheard when considering output power level control according to its active/actual master WSD interferes and its reduction method to reduce its number of interaction between the calculation engine and its connected WSDs are introduced. Finally, some numericalsimulation results and conclusions are summarized. The protection of adjacent services such as LTE systems in the 800 MHz band (Digital Dividend) for Region 1 is not studied in this clause. The focus is on the incumbent service operating in TV band.

Table 5: Comparison of different calculation methods

	Upper limit of master WSD output power level	System overhead	Calculation overhead
Fixed IM based method	Low	Low	Low
Flexible IM based method	Moderate	High	Moderate
Minimized IM method	High	High	High

4.2.2.1 Target scenario

Figure 24 shows an example of the target scenario. The three area types, which are an incumbent service coverage area, separation area, and white spaces, and the two kinds of WSDs, which are using frequency channel F1 and frequency F3, are presented. The separation area is the minimum distance between the incumbent service contour and white space operable area. The minimum distance could be defined by the WSD transmission configuration parameters like the transmission antenna height (this parameter should be known from the master WSD and its slave WSDs. However, if it is difficult to know the antenna height of the slave WSDs in a regulatory rule like FCC, the engine assumes its worst case of antenna height in accordance with the antenna height of the master WSD.), the maximum transmission power level, the number of potential interferes (this means the number of active WSDs in each operable channel which may transmit simultaneously.) in white spaces, etc. The distance is also dependent on the environment (urban, suburban or rural) and related propagation models.

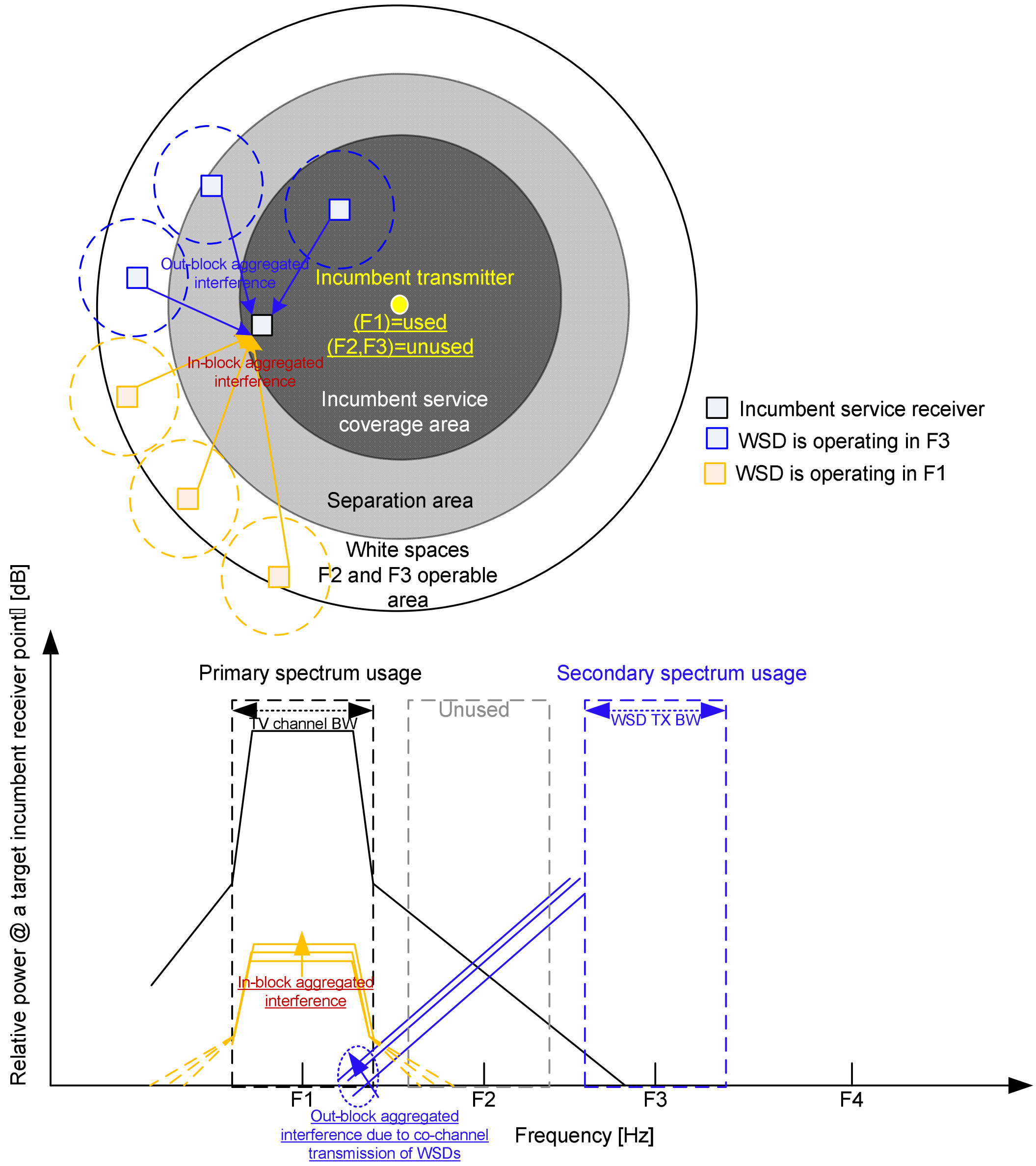


Figure 24: Target Use Case Example

In this scenario, the white space system tries to control the total amount of the neighborhood WSDs' emission level near to the incumbent service protection contour. It should be less than the allowable interference power level of incumbent receiver(s). Specifically, in a worst case scenario where multiple neighbouring white space networks are using same channel(s) and using a dissimilar radio access technology such as IEEE 802.11af [i.28], IEEE 802.22 [i.4] and ECMA 392 [i.31], the aggregated interference power level due to the simultaneous co-channel transmission will cause harmful interference for the incumbent receivers. This is because, any coexistence mechanism of existing radio access technologies, like coexistence beacon mechanism of IEEE 802.22 [i.4], are unable to address the coexistence of different radio access technologies.

One candidate solution to solve this problem is to adapt a network deployment, which is composed of a geolocation database, an advanced geolocation engine, and master/slave WSDs as shown in figure 25. In this scenario, only a white space network deployment based on master-WSD and slave-WSD configuration would be considered. It is necessary for the master WSD to have a responsibility to use network configuration parameters from an advanced geolocation engine, which will calculate maximum output power level information with the corresponding available channel list for each WSD in order to protect an incumbent receiver (and if necessary a receiver operating in an adjacent band) from a harmful interference. There will be several possible deployment scenarios for this engine. For example, this engine may be a part of geolocation database, or a separate engine from the geolocation database. In a case where it is a separate engine, a third party should take a responsibility to protect the incumbent service receivers from an aggregated interference problems Such third party engine may be also provide other services, such as coexistence services to the WSDs operating in the same area.

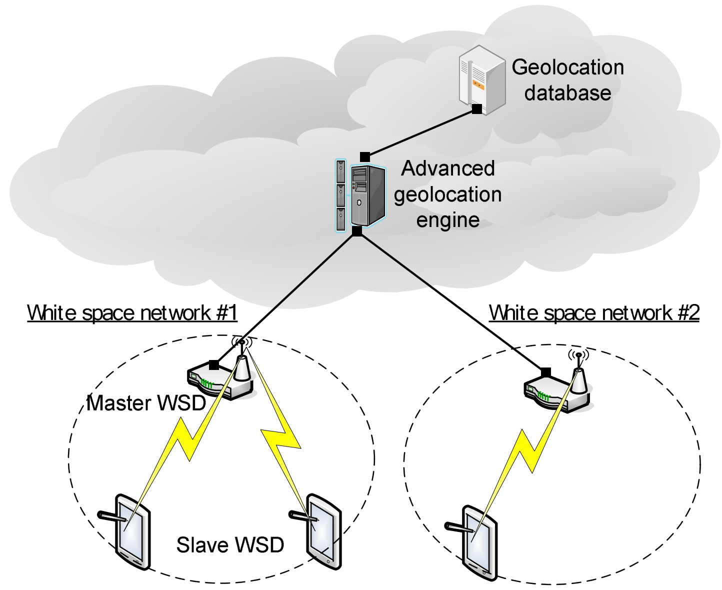


Figure 25: Network deployment scenario

4.2.2.2 Information Flow Among Relevant Entities

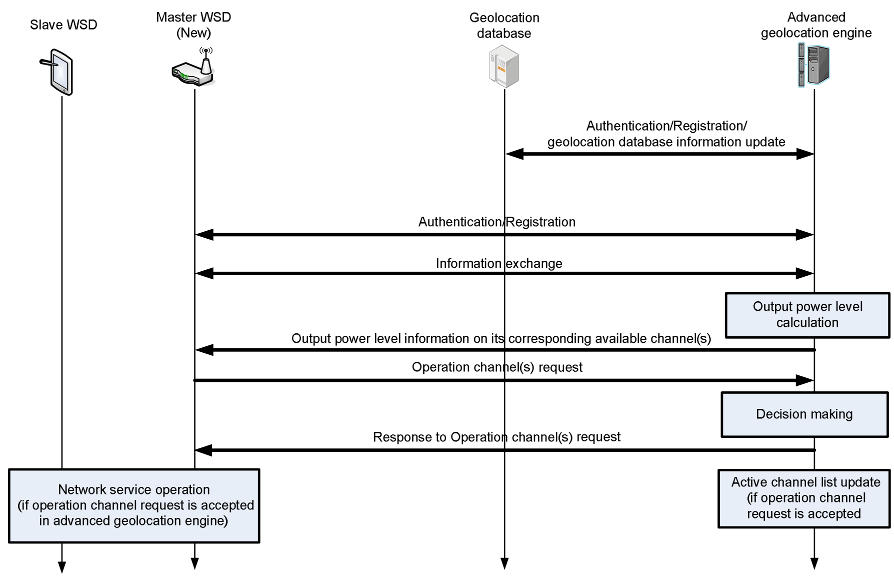


Figure 26: Information flow for output power level management

Figure 26 shows an example of the information flow of this target scenario. The following information exchange among geolocation database, advanced geolocation engine, and master WSD is the minimum requirement (the communication before the network service operation between the Master WSD and the Geolocation database/Advance geolocation engine and between the Master WSD and Slave WSDs will be investigated):

- From geolocation database to advanced geolocation engine:
  - Incumbents protection related parameters:
    - Geographical information for incumbents protection:
      - the closest reference point information (refer to Annex A); or
      - geographical information related to the incumbent protected contour.
    - The advanced geolocation engine finds the closest reference point candidate in accordance with the positioning information of each registered WSD:
      - or, advanced geolocation engine may be able to individually estimate the geographical information on the incumbent protected contour according to the analysis of the operable channel list for several position situations of WSDs.
    - Protection ratio or acceptable interference power level (if no, a fixed value will be defined in advance).
    - ACS (Adjacent Channel Selection) of incumbent receiver to be protected:
      - this information may be a different value for each incumbent receiver category in the reference point;
      - the ACS of systems using the adjacent bands should also be considered.
- From master WSD to advanced geolocation engine:
  - Master WSD and/or Slave WSDs IDs.
  - Location information.
  - Radio related parameters (ACLR, antenna height, antenna gain, beam-forming gain, maximum transmission power level, etc.):
    - ACLR (if no, estimate the potential worst value from the spectrum mask being defined by the regulatory basis):
      - This information may be a different value for every registered WSD.
      - Note that these transmitting parameters should also take into account the protection of the services working in the adjacent bands (for example the LTE system in the 800 MHz band in the Region 1).
- From advanced geolocation engine to master WSD:
  - For each WSD, available channel(s) with its corresponding location specific output power level (this output power may also be calculated to protect services in adjacent bands).
- Pre-installed information in advanced geolocation engine:
  - Propagation model related parameters (Path loss gain, shadowing margin, and fading margin).

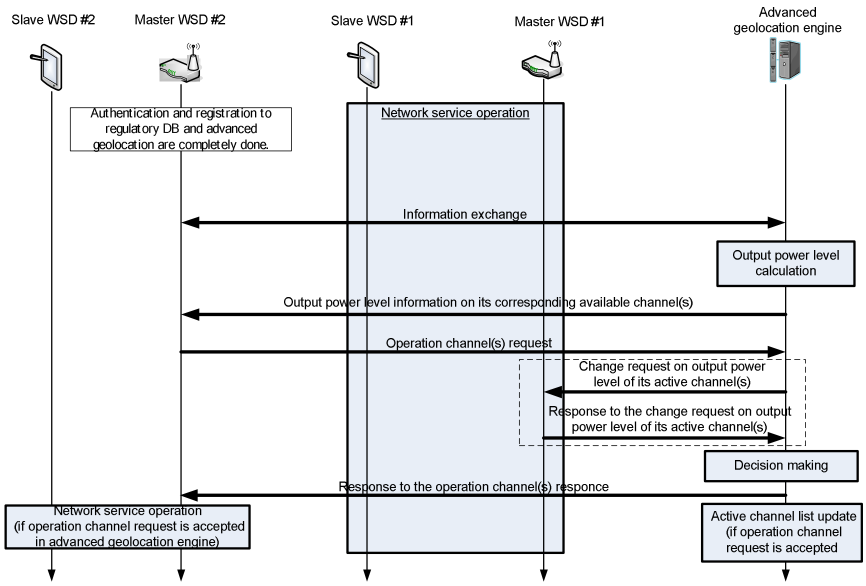


Figure 27: Information update flow for output power level management

An example of the information exchange for WSD output power level management is presented in figure 27. Based on the information exchange, the advanced geolocation engine calculates the location specific output power level information for each available channel for the WSD. After receiving this information, the master WSD choose the operation channel candidate, and request the channel use from the advanced geolocation engine. The advanced geolocation engine decide whether the request is accepted. While taking this decision, the advanced geolocation engine may request operation parameters changes at other WSDs in the area. If the request is accepted for the other WSD(s) which has(ve) already utilized the operation channel(s), the new WSD will be able to start its network service operation using the information in the response from the advanced geolocation engine. Subsequently, the advanced geolocation engine will update its active channel list and the information will be used for the next calculation event. If the request is not accepted for the other WSD(s) which has(ve) already utilized the operation channel(s), the new WSD will find the other candidate channel from its available channel list. This process will be run repeatedly until the approval is given by the advanced geolocation engine.

In addition to the example presented above, several other solutions to manage resource allocation for the WSDs could be possible. As an example the advanced geo-location engine may provide the operating parameters directly, or provide such information that there is no need to request changes in existing WSDs. In these cases the WSDs which appear later may get the worse parameters, and thus there may be need to reallocate all the WSDs after the available resources get too scarce.

The next clause introduces an example method to reduce such system overhead on the interface between the *IM* calculation engine and its connected WSDs by enabling output power control at each connected WSD taking into account the dynamically changing number of active/actual WSD interferers.

4.2.2.3 Analysis on the system overhead reduction when considering output power level control at each connected WSD taking into account the number of active/actual WSD interferes

The following situations could be considered as the reason why an additional interaction between the calculation engine and its connected WSDs will occur:

a) some of master WSDs in a given area will be deactivated; or

b) a new master WSD(s) enters in a given area.

In case of (a), the rest of the active master WSDs will be able to increase their maximum EIRP level due to the deactivation of neighbour master WSDs. However, it would be better off holding back the information exchange to update the maximum EIRPs between the calculation engine and the master WSDs in cases where the difference between the last updated maximum output power level (P_{tx}), and the maximum output power that will be applied ($P_{tx,temp}$ - $P_{M\arg in}$) is smaller than a threshold (dP_{tx}), or the current operation parameter is still enough for the use cases in the target WSD network. Subsequently, if the deactivation state of the master WSDs in geo-location database does not include the sleep mode and/or temporal power-off of the target master WSDs from a viewpoint of its power consumption, the interaction(signalling) between calculation engine and WSDs would be decreased in the management operation of geo-location database.

Similarly for the case of (b), the information exchange between the calculation engine and the master WSDs can be reduced in cases where the difference between the last updated maximum output power level (P_{tx}) and newly calculated maximum output power level ($P_{tx,temp}$) is smaller than the margin ($P_{M\arg in}$). It should be noted here that the goal in both scenario a) and b) is to always set the maximum output power utilized by the WSD a value of $P_{M\arg in}$ below the calculatedtransmit power in order to reduce the information exchange later on if a new WSD were to enter in a given area.

Summarizing the above considerations, the conditions whether the update of maximum output power level when the number of the active master WSDs is updated in a given area is necessary or not, it can be defined as follows:

$$\begin{Bmatrix} \text{If}\,((P_{tx} > P_{tx,temp})\ \text{or}\ (P_{tx,temp} > P_{tx} + P_{M\arg in} + dP_{tx})) \Rightarrow \text{Update}: P_{tx,new} = P_{tx,temp} - P_{M\arg in}, \\ \text{else}\ (P_{tx} \le P_{tx,temp} \le (P_{tx} + P_{M\arg in} + dP_{tx})) \Rightarrow \text{No update}\ (P_{tx,new} = P_{tx}) \end{Bmatrix}, \quad (14)$$

where:

P_{tx} : Last updated maximum output power level of the target master WSD.

$P_{tx,temp}$: Updated maximum output power level of the target master WSD.

$P_{tx,temp}$: Newly calculated maximum output power level of the target WSD according to the update of the number of active master WSDs in a given area.

dP_{tx} : Threshold to reduce the interaction between the calculation engine and its connected master WSDs in case of (a).

$P_{M\arg in}$: Margin value applied to the newly calculated maximum output power level in both cases a) and b) to take care of future newly_entering WSD in order to reduce the interaction between the calculation engine and its connected master WSDs.

Based on the criteria above, an interaction reduction method, to alleviate system overhead problem on the interface between the *IM* calculation engine and its connected WSDs in conducting output power control in accordance with its dynamic configuration change of active/actual WSD interferes, is proposed as shown in figure 28, and it is as follows:

STEP #1: If the calculation target master WSD is new entry in a given area, go to STEP #3. If no, go to STEP #2.

STEP #2: Retreive the current operating maximum EIRP level (P_{tx}) of the target master WSD, and go to STEP #3'. It is assumed this is known by the calculation engine and therefore no signalling is required.

STEP #3 (3'): Recalculation of the location specific maximum EIRP level ($P_{tx,\ temp}$) based on equation (11) in clause 5.2.4 of ECC Report 186 [i.23].

STEP #4: If the $P_{tx,\ temp}$ is smaller than the last updated maximum output power level (P_{tx}), go to STEP #6. If no, go to STEP #5.

STEP #5: If the $P_{tx,\ temp}$ is larger than the value of (P_{tx}+ P_{margin}+ dP_{tx}), go to STEP #6. If no, go to STEP #7.

STEP #6: Inform the update calculated maximum output power level ($P_{tx,\ new}$= $P_{tx,\ temp}$ - P_{margin}) to the target master WSD.

STEP #7: No update calculated to the target master WSD.

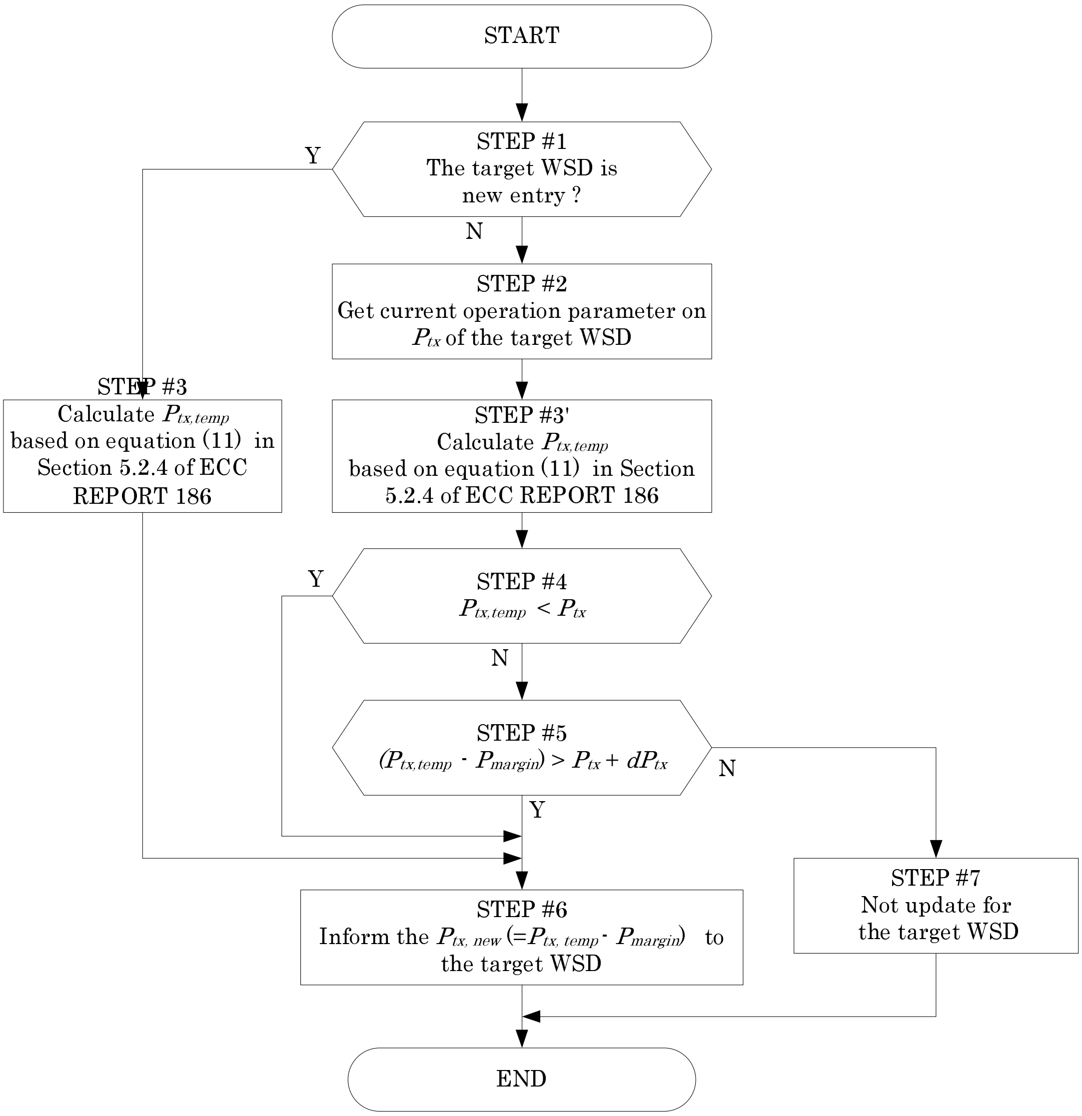


Figure 28: Updated procedure of Ptx of the calculation target master WSDs

According to the increase of the value dP_{tx}, the number of interaction in case of (a) will be decreased. However, the opportunity to increase the maximum EIRP of the target WSDs will be lost so there will be some impacts for the network capacity of the WSD. Similarly for case (b), according to the increase of the value $P_{M\arg in}$, the number of interactions will be decreased. However, the maximum EIRP of the target WSDs is decreased by $P_{M\arg in}$ value settings, so there will be some impact to the network capacity of the WSD.

Therefore, next clause tries to see the impacts on the system overhead using computer simulation when the dP_{tx} ($P_{M\arg in}$) value setting to reduce the interaction between the calculation engine and its connected WSDs is adopted in considering the dynamic change of the number of active master WSDs in a given area.

4.2.2.4 Numerical simulation results

4.2.2.4.1 Simulation methodology

Figure 29 shows the simulation methodology. Figure 30 shows the geo-location information related parameters of the distributed master WSDs. The simulation parameters based on ECC Report 159 [i.3] are shown in table 6. The simulation methodology is as follows:

STEP 1: Set the incumbent service operation parameters:

- The parameters in the table 1 of clause 4.1 of ECC Report 159 [i.3] are adopted.

STEP 2: Calculate the protection area of the incumbent service operation and the protection contour:

- The protection contour is calculated based on the method in clause 4.1 of ECC Rreport 159 [i.3].

STEP 3: Set the number of distributed master WSDs and its geo-location related parameters of the master WSDs:

- The following parameters related to the geo-location information of the master WSD are considered in this simulation:
    - Protection distance (D_1 [km]):
        - This parameter is required in considering the interference effects from the slave WSD in each WSD network managed by each master WSD.
    - Separation distance (D_2 [km]) of each master WSD:
        - Each master WSD is located to a distributed point where is separation distance (D_2 [km]) away from each other as shown in figure 30.

STEP 4: Set the WSD network operation parameters managed by each master WSD:

- TRX configuration parameters such as antenna height and antenna gain are set to be here. The detail simulation parameters are shown in table 6.

STEP 5: Calculate the location specific output power level of each master WSD:

- Three kinds of *IM* calculation method defined in ECC Report 186 [i.23], clause 5.2.4 are adopted here. The detail simulation parameters are shown in table 6.
- The reduction method of the interaction between the calculation engine and WSDs, based on figure 28, is adopted in a case where flexible/minimized IM calculation method is adopted.

STEP 6: Set additional master WSDs in the given area:

- All the master WSDs are distributed so as not to be overlapping in same geo-location point as each other.

STEP 7: Recalculate the location specific output power level of each master WSD:

- The reduction method of the interaction between the calculation engine and WSDs, based on figure 28, is adopted in a case where flexible/minimized IM calculation method is adopted.

STEP 8: Count the number of interactions between the calculation engine and WSDs in adopting the fixed/flexible/minimized IM calculation methods.

STEP 9: Collect the simulation results on the SINR of the protection contour, the maximum output power level of WSD and its network area capacity [bits/Hz] in each WSD network by each master WSD.

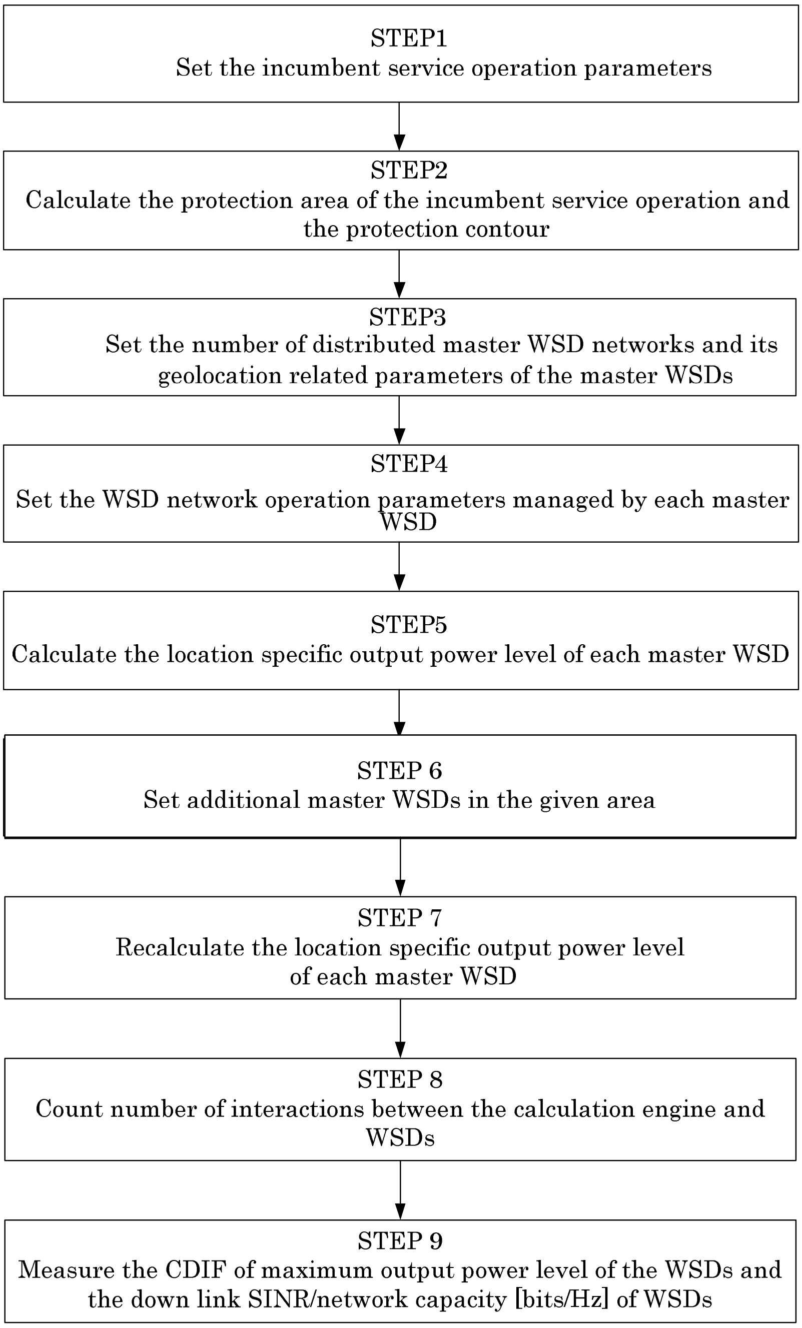


Figure 29: Simulation methodology

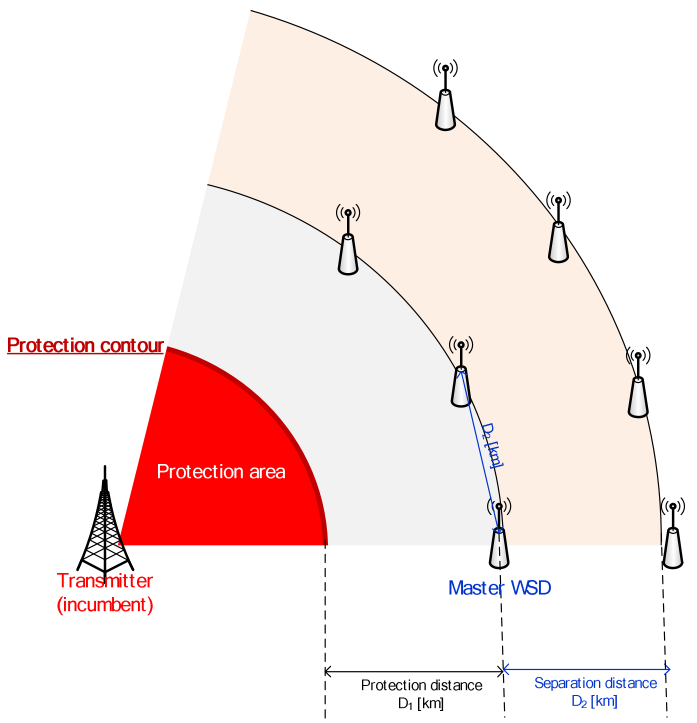


Figure 30: Geo-location information related parameters

Table 6: Simulation parameters

Parameter	Value
Frequency-related parameters	
Frequency	600 MHz
Number of channels	10
Channel bandwidth	7,6 MHz
Channel separation	8 MHz
ACLR (= $ACLR^{WSD}(f_{WSD} - f_{BS})$	ACLR: 33 dB for all adjacent channels ACS: 61 dB
ACS (= $ACLR^{BS}(f_{WSD} - f_{BS})$	
Geo-location-related parameters	
Protection contour from incumbent transmitter	52,9 km
Protection distance (=D_1)	20 km
Separation distance (=D_2)	2 km
Reference point selection criteria for incumbent service protection	Regarding the calculation step in fixed/flexible method, the closest point in the protection contour of the incumbent service should be chosen as the reference point of each target master WSD. Regarding the calculation step in minimized method, the closest point in the protection contour of the incumbent service should be chosen for the reference point of each target master WSD in the first calculation step. After that, the calculation engine will try to find the most severe interfere-victim reference point of each WSD to adjust the output power of WSDs while considering in-block/out-block interference effects from multiple WSDs
Number of active master WSDs at a time t	300
Number of increased active master WSDs from time $t-1$ to t	10, 30 or 100 Note that the number of active master WSDs at *t-1* are 290, 270 and 200, respectively. Different intial values will lead to different output power levels in tables 8 - 10.

Parameter	Value
Range of angle where master WSD are distributed	0 - 180 degrees
Number of slave WSDs which is located in an area of (D_2/2) [km] away from the geo-location point of each master WSD	500
Distribution of geo-location points of slave WSDs	Uniform distribution on the radius of 0,5 [km] away from the geo-location point of master WSD
Propagation-related parameters	
BS broadcaster antenna height	200 m
BS receiver antenna height	10 m
Master WSD antenna height	20 m
Slave WSD antenna height	10 m
$m_{G(dB)}$	
Propagation model	Recommendation ITU-R P.1546-4 [i.6] (Rural, Time percentage = 1 %)
BS receiver antenna directivity discrimination with respect to WSD (D_{dir})	16 dB
TV receiver antenna gain (= G_i)	12,15 dB
TV receiver feeder loss (= L_f)	3 dB
BS receiver polarization discrimination with respect to the WSD signal (D_{pol})	0 dB
Output power-related parameters	
WSD location specific output power calculation methods	Fixed method, Flexible method and Flexible minimized method defined in ECC Report 186 [i.23], clause 5.2.4
Limit of WSD output power	36 dBm
Standard deviation of BS power at receiver σ_{BS}	5,5 dB
Standard deviation of coupling gain between incumbent receiver and WSD transmitter σ_{WSD}	3,5 dB
Location probability (*LP*) without interference from WSD q_1	95 %
LP with interference from WSD q_2	94,9 %
Acceptable degradation ΔLP(= q1 - q2)	0,1 %
WSD safety margin *SM* (including fading margin)	$\sqrt{2}erfc^{-1}\left[2\left(1-\frac{q_2}{q_1}\right)\right]\sqrt{\sigma_{BS}^2+\sigma_{WSD}^2}$
TV broadcaster transmission power	79,15 dBm/channel
Interaction reduction related parameter	
Interaction reduction margin P_{Margin} Note that we set dP_{tx} equal to 0 dB in order to show the effect of P_{Margin}.	0, 1 or 3 dB
Noise-related parameters	
Noise density	-174 dBm/Hz
Noise figure	7 dB for all nodes
Aggregated interference power level related parameters	
Multiple interference margin: $IM_{(dB)}$ (Fixed method)	10*log10 (Potential maximum number of active master WSDs in each available channel which depends on the simulation parameter setting in allocating active WSDs in available channels)
Multiple interference margin: $IM_{(dB)}$ (Flexible method)	10*log10 (Maximum number of all the number of active master WSDs in each available channel)
Incumbent service operation parameters	
Minimum incumbent service (BS) power @ receiver $m_{z_{(dB)}}$	-77,1 dBm
Protection ratio $r(\Delta f)_{(dB)}$	23,1 dB

Table 7: Network capacity calculation related parameters

Network capacity calculation related parameters	
Definition of the network coverage in calculating network capacity of each master WSD	Calculating the down link network capacity between each master WSD and its slave WSDs which are distributed on the radius of 0.5[km] away from the geo-location point of master WSD itself
Resource allocation method for each slave WSD in an area of (D_2/2) [km] away from the geo-location point of master WSD itself	Centric resource allocation method via TDD-TDMA (No access collision is considered)
Network coexistence protocol (i.e. coexistence beacon mechanism of IEEE 802.22 [i.4]) among neighbor networks managed by each master WSD	N/A
Channel selection method of each master WSD	Random selection
Reference node of potential interferes for incumbent service receiver in each WSD network	Each master WSD
Interference among WSD networks	Considered
Transmission power level of slave WSDs	N/A (Because the downlink transmission is only simulated here)

4.2.2.4.2 Simulation results

The comparison results of average interaction occurrence probability for update of WSD output power level (Number of TVWS channels = 5 and 10) is shown in figure 31 and its upper limit of master WSD, CDFs of SINR and downlink capacity are shown in tables 8 to 10, respectively.

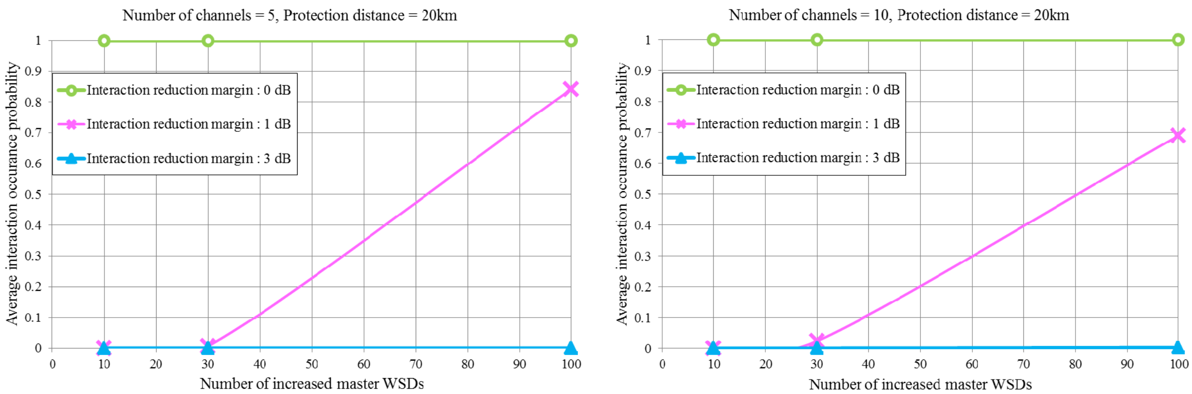


Figure 31: Average interaction reduction probability in case of protection distance = 20 km for 5 and 10 channels

Table 8: Comparison of performance of master WSD (Master-Slave distance = 0,5 km, Number of increased master WSD = 10)

Total number of master WSDs_ (including newly-entering master WSDs)		300					
Number of increased master WSDs		10					
Protection distance (km)		20					
Master-Slave distance (km)		0,5					
Number of channels		5			10		
Output power calculation method		**Fixed**	**Flexible**	**Flexible minimized**	**Fixed**	**Flexible**	**Flexible minimized**
Output power level of master WSD (dBm)	5 % CDF	10,5	16,5	22,5 (P_{Margin} = 0 dB) 21,5 (P_{Margin} = 1 dB) 19,5 (P_{Margin} = 3 dB)	10,5	19,0	24,5 (P_{Margin} = 0 dB) 23,6 (P_{Margin} = 1 dB) 21,6 (P_{Margin} = 3 dB)
	50 % CDF	12,3	18,5	24,6 (P_{Margin} = 0 dB) 23,6 (P_{Margin} = 1 dB) 21,6 (P_{Margin} = 3 dB)	12,3	21,0	26,6 (P_{Margin} = 0 dB) 25,7 (P_{Margin} = 1 dB) 23,7 (P_{Margin} = 3 dB)
SINR of WSD (dB)	5 % CDF	-10,1	-3,8	1,9 (P_{Margin} = 0 dB) 1,0 (P_{Margin} = 1 dB) -0,8 (P_{Margin} = 3 dB)	-10,0	-1,2	4,1 (P_{Margin} = 0 dB) 3,3 (P_{Margin} = 1 dB) 1,5 (P_{Margin} = 3 dB)
	50 % CDF	-1,1	5,1	10,5 (P_{Margin} = 0 dB) 9,7 (P_{Margin} = 1 dB) 7,9 (P_{Margin} = 3 dB)	-0,9	7,7	12,9 (P_{Margin} = 0 dB) 12,1 (P_{Margin} = 1 dB) 10,3 (P_{Margin} = 3 dB)
Network capacity of WSD [bps/Hz]	5 % CDF	0,1	0,5	1,4 (P_{Margin} = 0 dB) 1,2 (P_{Margin} = 1 dB) 0,9 (P_{Margin} = 3 dB)	0,1	0,8	1,8 (P_{Margin} = 0 dB) 1,7 (P_{Margin} = 1 dB) 1,3 (P_{Margin} = 3 dB)
	50 % CDF	0,8	2,1	3,6 (P_{Margin} = 0 dB) 3,4 (P_{Margin} = 1 dB) 2,9 (P_{Margin} = 3 dB)	0,9	2,8	4,4 (P_{Margin} = 0 dB) 4,1 (P_{Margin} = 1 dB) 3,6 (P_{Margin} = 3 dB)

Table 9: Comparison of performance of master WSD (Master-Slave distance = 0,5 km, Number of increased master WSD = 30)

Total number of master WSDs (including newly-entering master WSDs)		300					
Number of increased master WSDs		30					
Protection distance (km)		20					
Master-Slave distance (km)		0,5					
Number of channels		5			10		
Output power calculation method		**Fixed**	**Flexible**	**Flexible minimized**	**Fixed**	**Flexible**	**Flexible minimized**
Output power level of master WSD (dBm)	5 % CDF	10,5	16,5	22,5 ($P_{M\arg in}$ = 0 dB) 21,8 ($P_{M\arg in}$ = 1 dB) 19,9 ($P_{M\arg in}$ = 3 dB)	10,5	19,0	24,5 ($P_{M\arg in}$ = 0 dB) 23,7 ($P_{M\arg in}$ = 1 dB) 21,8 ($P_{M\arg in}$ = 3 dB)
	50 % CDF	12,3	18,5	24,6 ($P_{M\arg in}$ = 0 dB) 23,9 ($P_{M\arg in}$ = 1 dB) 21,9 ($P_{M\arg in}$ = 3 dB)	12,3	21,0	26,6 ($P_{M\arg in}$ = 0 dB) 25,9 ($P_{M\arg in}$ = 1 dB) 23,9 ($P_{M\arg in}$ = 3 dB)
SINR of WSD (dB)	5 % CDF	-10,1	-3,8	1,9 ($P_{M\arg in}$ = 0 dB) 1,3 ($P_{M\arg in}$ = 1 dB) -0,5 ($P_{M\arg in}$ = 3 dB)	-10,0	-1,2	4,1 ($P_{M\arg in}$ = 0 dB) 3,5 ($P_{M\arg in}$ = 1 dB) 1,7 ($P_{M\arg in}$ = 3 dB)
	50 % CDF	-1,1	5,1	10,5 ($P_{M\arg in}$ = 0 dB) 9,9 ($P_{M\arg in}$ = 1 dB) 8,2 ($P_{M\arg in}$ = 3 dB)	-0,9	7,7	12,9 ($P_{M\arg in}$ = 0 dB) 12,3 ($P_{M\arg in}$ = 1 dB) 10,5 ($P_{M\arg in}$ = 3 dB)
Network capacity of WSD [bps/Hz]	5 % CDF	0,1	0,5	1,4 ($P_{M\arg in}$ = 0 dB) 1,2 ($P_{M\arg in}$ = 1 dB) 0,9 ($P_{M\arg in}$ = 3 dB)	0,1	0,8	1,8 ($P_{M\arg in}$ = 0 dB) 1,7 ($P_{M\arg in}$ = 1 dB) 1,3 ($P_{M\arg in}$ = 3 dB)
	50 % CDF	0,8	2,1	3,6 ($P_{M\arg in}$ = 0 dB) 3,4 ($P_{M\arg in}$ = 1 dB) 2,9 ($P_{M\arg in}$ = 3 dB)	0,9	2,8	4,4 ($P_{M\arg in}$ = 0 dB) 4,2 ($P_{M\arg in}$ = 1 dB) 3,6 ($P_{M\arg in}$ = 3 dB)

Table 10: Comparison of performance of master WSD (Master-Slave distance = 0,5km, Number of increased master WSD = 100)

Total number of master WSDs (including newly-entering master WSDs)		300					
Number of increased master WSDs		100					
Protection distance (km)		20					
Master-Slave distance (km)		0,5					
Number of channels		5			10		
Output power calculation method		**Fixed**	**Flexible**	**Flexible minimized**	**Fixed**	**Flexible**	**Flexible minimized**
Output power level of master WSD (dBm)	5 % CDF	10,5	16,5	22,5 ($P_{M\arg in}$ = 0 dB) 21,6 ($P_{M\arg in}$ = 1 dB) 19,9 ($P_{M\arg in}$ = 3 dB)	10,5	19,0	24,5 ($P_{M\arg in}$ = 0 dB) 23,6 ($P_{M\arg in}$ = 1 dB) 21,9 ($P_{M\arg in}$ = 3 dB)
	50 % CDF	12,3	18,5	24,6 ($P_{M\arg in}$ = 0 dB) 23,6 ($P_{M\arg in}$ = 1 dB) 22,2 ($P_{M\arg in}$ = 3 dB)	12,3	21,0	26,6 ($P_{M\arg in}$ = 0 dB) 25,7 ($P_{M\arg in}$ = 1 dB) 24,2 ($P_{M\arg in}$ = 3 dB)
SINR of WSD (dB)	5 % CDF	-10,1	-3,8	1,9 ($P_{M\arg in}$ = 0 dB) 1,1 ($P_{M\arg in}$ = 1 dB) 0,0 ($P_{M\arg in}$ = 3 dB)	-10,0	-1,2	4,1 ($P_{M\arg in}$ = 0 dB) 3,4 ($P_{M\arg in}$ = 1 dB) 2,1 ($P_{M\arg in}$ = 3 dB)
	50 % CDF	-1,1	5,1	10,5 ($P_{M\arg in}$ = 0 dB) 9,7 ($P_{M\arg in}$ = 1 dB) 8,7 ($P_{M\arg in}$ = 3 dB)	-0,9	7,7	12,9 ($P_{M\arg in}$ = 0 dB) 12,1 ($P_{M\arg in}$ = 1 dB) 11,0 ($P_{M\arg in}$ = 3 dB)
Network capacity of WSD [bps/Hz]	5 % CDF	0,1	0,5	1,4 ($P_{M\arg in}$ = 0 dB) 1,2 ($P_{M\arg in}$ = 1 dB) 1,0 ($P_{M\arg in}$ = 3 dB)	0,1	0,8	1,8 ($P_{M\arg in}$ = 0 dB) 1,7 ($P_{M\arg in}$ = 1 dB) 1,4 ($P_{M\arg in}$ = 3 dB)
	50 % CDF	0,8	2,1	3,6 ($P_{M\arg in}$ = 0 dB) 3,4 ($P_{M\arg in}$ = 1 dB) 3,1 ($P_{M\arg in}$ = 3 dB)	0,9	2,8	4,4 ($P_{M\arg in}$ = 0 dB) 4,1 ($P_{M\arg in}$ = 1 dB) 3,8 ($P_{M\arg in}$ = 3 dB)

One can conclude that the impact on the WSD network performance when the change in interaction reduction margin ($P_{M\arg in}$) from 0 dB] to 3 dB is adopted in calculating the location specific output power level of target WSDs as follows:

1) There is no impact on the relationship between *IM* calculation methods and the WSD network performance such as maximum WSD output power level, SINR and network capacity, when different interaction reduction margin ($P_{M\arg in}$) values are adopted for flexible/minimized *IM* calculation methods. The consideration of the number of active WSDs of each available channel in the *IM* calculation engine will bring us much higher communication opportunity of WSDs than the case where the fixed/predetermined *IM* calculation method without considering the number of active WSDs of each available channel is adopted, and the minimized *IM* calculation method can show the highest performance in three methods.

2) The degradation of WSD network performance due to the interaction reduction margin setting seems to be negligibly small. For example, when one consider that the increased rate of new master WSDs' entry in a given area is about 30 % of the total number of active master WSDs (300) in the given area, there would be almost no necessity to conduct any interaction between the calculation engine and its connected WSDs, if the interaction reduction margin ($P_{M\arg in}$) is 3,0 dB. Nevertheless, the WSD network performance of the flexible/minimized *IM* calculation method can still be kept around 6 dBm higher than the one with the fixed/predetermined *IM* calculation method at 5 % CDF of location specific maximum WSD output power level. Subsequently, the WSD network performance of the minimized *IM* calculation method can still be kept at around 3 dBm greater than the one of the flexible *IM* calculation method at 5 % CDF of location specific maximum WSD output power level.

4.2.2.5 Conclusions

The target scenario, its system model for the feasibility study on output power control techniques of WSDs based on an aggregated interference margin (*IM*) setting defined in ECC Report 186 [i.23], clause 5.2.4 and its information flow among relevant entities for output power control techniques of WSDs were first introduced. Next, some studies on the issues, where the system overhead will increase due to the dynamic change of the number of active master WSDs in each available channel in calculating location specific maximum WSD output power level defined in ECC Report 186 [i.23], clause 5.2.4, were conducted. An additional margin setting approach for reducing the number of interaction beween the calculation engine and its connected WSDs according the dynamic change of active interferes to reduce its system overhead was proposed in clause 5.2.2.3. Simulation results showed that the proposed method would be quite effective in achieving performances of output power control techniques of WSDs defined in ECC Report 186 [i.23] by reducing its system overhead (=the number of interaction between the calculation engine and its connected WSDs).

4.3 Combined Sensing and Geo-location Database Design

4.3.1 General

The current sensing technology has not been proven to be sufficient to discover incumbent services. In addition, it requires complex implementation which is not feasible for most WSDs. Thus, the sensing should not be defined as a mandatory requirement for WSDs. However, the sensing may optionally be used with the geo-location database access to retrieve more information on RF spectrum use. As an example, the WSD may perform sensing to discover other WSD operation, and thus to better coexist with other WSDs or incumbent services. Possibly, also the geo-location database may allow operation in some channels and geo-locations, e.g. where local white space may exist, pending on the WSD capability for sensing. The geo-location database may assist the WSDs in such sensing.

4.3.2 Combined geo-location and sensing for identification of the available spectrum

Combined geo-location and sensing can be used in order to determine the usable frequencies on which to transmit as well as the EIRP to be used by a WSD. Such combined geo-location and sensing can provide additional protection to the incumbent as well as more reliable identification of the available spectrum. For example, a device which uses sensing may do so only in the case where the database has allowed or required such operation in order to further identify the availability of the channel at a particular location. In addition, the database could avoid any potentially harmful effects from aggregated interference by limiting the number of devices that can operate using sensing in a specific area or channel or forcing them to use significantly reduced transmit power.

The techniques for the use of combined geolocation and sensing will depend heavily on the regulatory framework in which these mechanisms are applied. This clause explores some techniques used for different regulatory frameworks.

4.3.2.1 Example use of combined sensing and geo-location applied to the FCC regulatory framework

4.3.2.1.1 FCC regulatory framework

As part of the second memorandum opinion and order released by the FCC (FCC 10-174 [i.1]), Fixed devices, Mode I and Mode II personal/portable devices (see chapter 6 for device classes), and sensing-only devices were introduced. Access to TVWS channels by TV band wireless devices was allowed by devices having geo-location capabilities and database access (so-called fixed devices or Mode II personal/portable devices) or devices operating on channels that are chosen by such devices (so-called Mode I personal portable devices). The FCC also allows access to TVWS channels by sensing only devices: devices not having access to a database or to a Fixed or Mode II personal/portable device (that can relay the database information). Such sensing-only devices rely on sensing information to determine the availability of a channel and the sensing is performed locally at each sensing-only device. In other words, sensing information from one device cannot be used for decision making at another device. Although the use of sensing only devices has been allowed by the FCC, support for sensing is not a mandatory requirement, as incumbent information might be available from the geolocation database. Sensing only devices are subjected tests, approval, and product certification which are still to be defined by the FCC.

In [i.1] the availability of a channel is determined through the definition of protected signal contours that surround TV stations and defining a "no-transmission" area based predominately on signal propagation characteristics.

The clauses which follow present a method for using combined geo-location and sensing using the FCC regulatory framework as an example.

4.3.2.1.2 Main operation

The main limitation of the mechanism for defining the FCC signal contours is that it does not take into account spectrum which may be available locally in homes or under the influence of shadowing from hilly terrain or buildings, as these obstacles can provide significant signal attenuation, allowing transmission at a reduced distance from the TV transmission station.

According to the FCC ruling, devices determine the availability of channels based on information from a geo-location database. If a device does not have access to the database, it may use the TVWS if it obeys the rules associated with sensing-only devices.

These two distinct modes of operation defined by the FCC (database access and sensing-only) could potentially be combined to define a new mode of operation which would make use of both database information and sensing. In this new potential mode of operation, by default a device (or network) will utilize channels that are specified to be free based on the database information without the need to perform sensing. However, if the required number of channels needed by a device (or network) is not satisfied, the device (or devices in the network) may optionally (if it supports sensing) act as a sensing only device and search for additional incumbent-free channels among those specified as occupied by the database. This may allow the device to potentially find additional available spectrum, subject to operation according to the rules of a sensing-only device.

It may then operate as a sensing-only device (with reduced transmission power) on those incumbent-free channels discovered by sensing. When a device acts in sensing only mode it will have the ability to vacate a channel that was selected in this mode when a primary user is detected. As a result, the FCC rules imposed on the sensing in this example are those of reduced transmission power and channel monitoring and evacuation requirements. Since additional rules are not built in to the FCC framework, this method is subject to the same limitations of the sensing only device class defined by the FCC, i.e. reliability of the sensing results based on FCC's required sensitivity levels of -107 dBm for wireless microphone and -114 dBm for DTT. Since sensing is assumed to not be a requirement, a device may chose to not behave in this way, and utilize only the results from the database.

Given that both database and sensing information is being used by a device, the database information can also be used to reduce the overall sensing time. Upon registering with the geo-location database, the base station (eNB in the case of LTE or Wi-Fi Access Point) receives channel occupancy information. In a given location the channel occupancy information may indicate the specific type of (licensed) incumbent user for which the channel has been reserved. For instance, the database may indicate that a TV broadcast, or a wireless microphone system occupies a channel. This information can be made available to devices operating in sensing mode as described above. Although this additional information does not improve the sensing as such (sensing performance is still limited by the minimum sensitivity it needs to achieve), it will reduce the complexity of sensing for these devices, as a device will only need to monitor the channel for one type of incumbent user. This simplification may allow for a reduction in sensing time in the sensing only device and, depending on how devices are implemented, may result in an increase in network throughput. Finally, as sensing time is reduced through this method, power consumption at each of the sensing only devices may be reduced and (licensed) incumbent user detection time may also be reduced as devices will focus on sensing for the incumbent users it knows can occupy a given channel.

4.3.2.1.3 Information flows among relevant entities

Upon initial use of the TVWS, or the need for additional bandwidth, a device or network will need to perform an initial channel selection procedure. In addition, a channel switch may be triggered by the detection of an incumbent user or poor channel quality in a specific channel. The information flows for each scenario are shown below. In the information flows below, it is assumed that the Mode I and Mode II devices have already been certified as sensing only devices.

1) Channel Selection Information Flow:

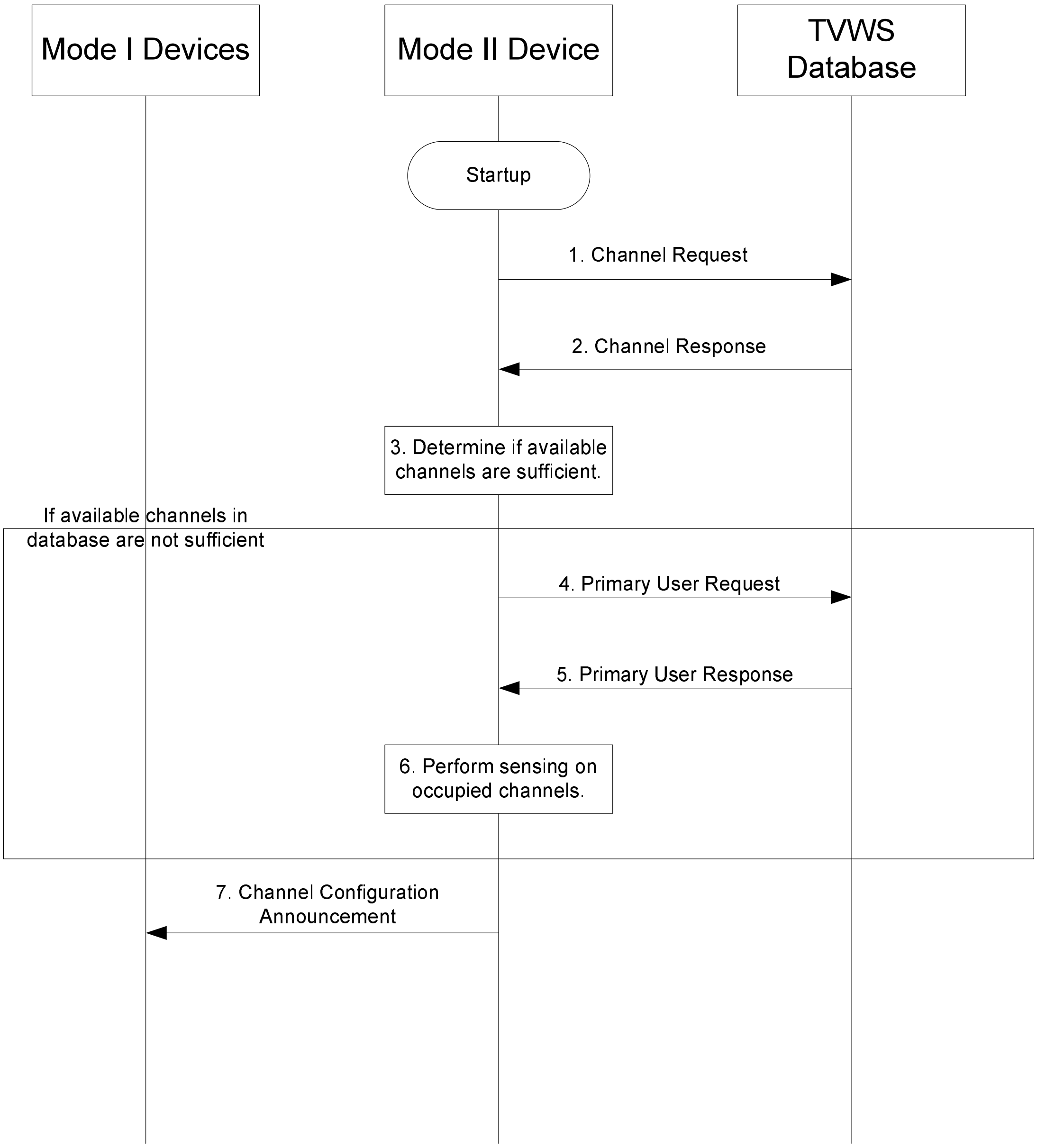


Figure 32: Channel Selection Information Flow

1. Following startup, the Mode II device queries the TVWS database for a list of available channels in order to find channel(s) on which the system can operate.

2. The TVWS database returns a list of available channels in the TVWS band. These are channels that the devices are able to use without the need for sensing.

3. Based on the available channels returned by the TVWS database, the Mode II device determines whether there are a sufficient number of available channels to support its required/desired operation.

4. If the number of available channels as per the database is insufficient or the Mode II device would like to utilize additional channels, it requests the information about the primary user that is currently occupying the channels which the database initially indicated as occupied. The database may additionally indicate which channels may be most suitable for trying to operate in sensing-only mode. This information could optionally have been sent in step 2.

5. The TVWS database sends the primary user information (DTT or wireless microphone) for each of the occupied channels.

6. The Mode II device performs sensing on the channels indicated as occupied by the TVWS database and determines which of these (if any) are unoccupied in its specific location based on sensing results (in which case, it can operate on them in sensing only mode). The sensing results could optionally be sent to the database to provide it with additional information.

7. The Mode II device sends or broadcasts the channels to be used by the system to the Mode I devices which can communicate with it, including whether the Mode I device needs to operate as a sensing only device on any given channel and which primary user should be sensed in this case. In some cases, this information needs to be transmitted using secure methods/protocols, since it may contain information about the primary user system channel usage.

When operating on channels initially indicated as occupied by the TVWS database, both Mode I and Mode II devices operate as sensing-only devices (regular sensing should be performed).

2) Channel Switch Information Flow:

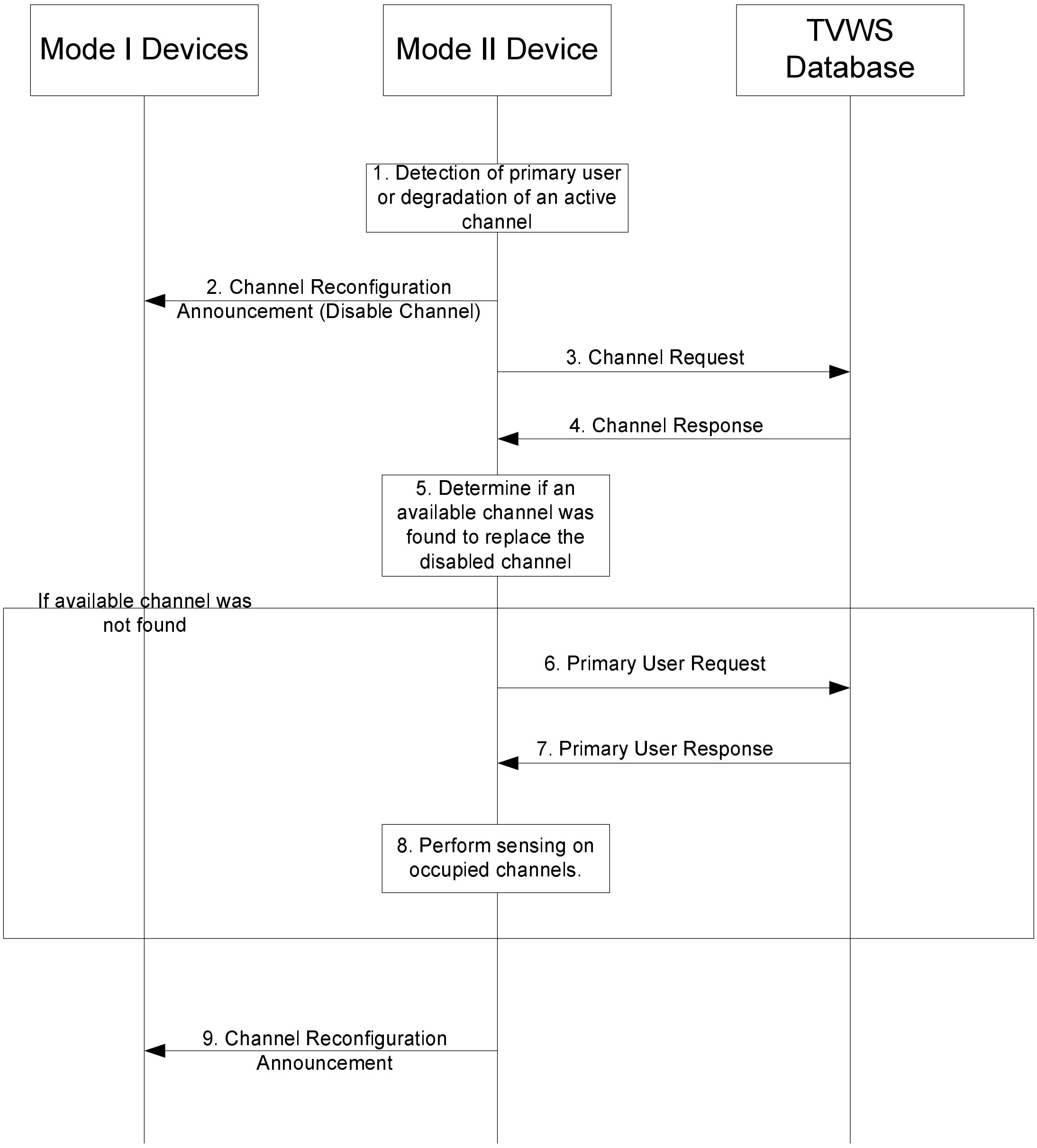


Figure 33: Channel Switch Information Flow

1. The Mode II device may decide to change the operation on a particular TVWS channel due to the degradation of quality on that channel, or, because it has detected through sensing the presence of a primary user (for channels where operation is sensing only).

2. If possible, the Mode II device may decide to communicate immediately (rather than waiting for the selection of a replacement channel) to its attached Mode I devices the need to stop using the channel affected by the degradation or arrival of a primary user. This would be advantageous, for instance, in order to reduce the impact on the primary user or to satisfy the 2 second channel move time required by the FCC. The detection of a primary user may come from a Mode I device as well, in which case the Mode I device could send the channel Channel Reconfiguration Announcement, or notify the Mode II device to trigger the announcement.

3. The Mode II device makes a request to the TVWS database (as in the channel selection information flow).

4. The TVWS database responds with a list of available channels (as in the channel selection information flow). These channels can be used by the devices without the need for sensing.

5. The Mode II device uses the information received from the TVWS database to determine whether a replacement channel is available.

6. As in the channel selection information flow, if no available channels were found to serve as a replacement channel, the Mode II device requests the information about the primary users on occupied channels. The database may also indicate which channels may be most suitable for trying to operate in sensing-only mode.

7. The database responds with the information about the primary users on the occupied channels (as in the channel selection information flow).

8. The Mode II device performs sensing on the occupied channels using the knowledge of the primary user (as in the channel selection information flow) until it finds a channel that can be used as a replacement in its specific location. The sensing results could optionally be sent to the database to provide it with additional information.

9. If a replacement channel is found, this information is conveyed to each of the attached mode I devices.

4.3.2.2 Use of primary user sensing capability for system channel allocation

If there is additional information provided by the geolocation database it may be possible to have devices which support only one type of primary user detection (DTT or wireless microphone) to still operate in sensing only mode on certain channels. Development of such restricted sensing devices may be advantageous from a device manufacturer point of view. In particular, sensing for a specific incumbent (e.g. by using feature detection) may require complex sensing HW.

EXAMPLE 1: Wireless microphone sensing may not be able to use certain pilot sequences that are defined in the case of DTT, resulting in more complex hardware required to achieve the same detection performance.

As a result, certain manufacturers may want to build only limited or no sensing capabilities at all into a specific device due to cost or reasons related to field of expertise. Channels can then be allowed to a device or list of device depending on whether the device supports the sensing required for operation on a channel in sensing only mode.

In order to manage the useable list of channels, a central entity may be used to obtain the information from the Geo-location Database and manage that information across a network. In this case, it is therefore assumed that a "Central Control Point (CCP)" controls, configures, and manages the operation of the TVWS system. The CCP obtains channel information from a Geo-location Database and uses it to control and configure the Access Points (AP). This is depicted in figure 34 for the case of a WLAN AP. The remainder of the clause assumes the use of WLAN.

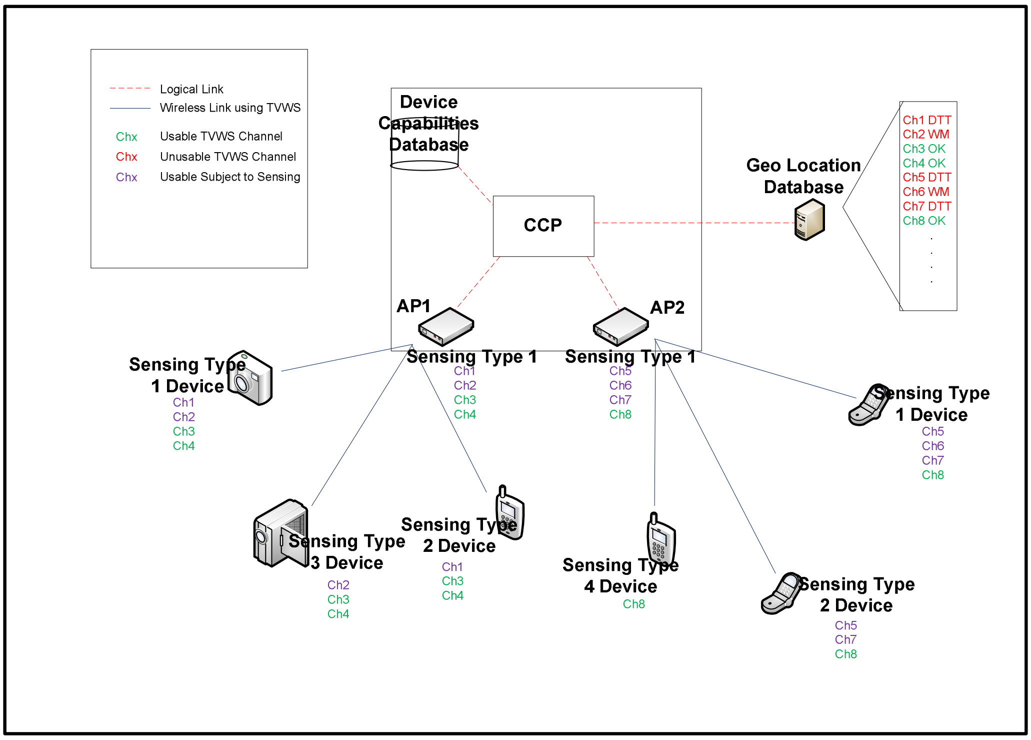


Figure 34: System description of TVWS system operation based on sensing capability

From the current regulatory perspective, the CCP would need to be integrated into the geo-location database itself, or would be a logical entity that is distributed in the APs themselves and allows for selection of channels among the different APs. In particular, this would allow the APs to act as master devices (or Mode II devices in the context of the FCC) and therefore contact the database directly. On the other hand, the devices connected to the APs would be slave devices (or Mode I devices in the context of the FCC). For the sole purpose of illustrating the technique, it is assumed that the CCP has some coordinating role in assigning the channels from the information in the geolocation database, and that it could take on any of the two forms indicated above but also be a centralized management entity which accesses the geo-location databases on behalf of the master (mode II) devices.

To allow the CCP to efficiently allocate channels, the CCP can classify devices based on the sensing capabilities of the device such as the type of registered primary users the device can sense and detect. The CCP may store this information in its own local database (shown above as the device capability database). For example in TVWS and in the context of the current FCC regulation, the geolocation database could be extended from what it currently provides so that it indicates the primary user that is occupying a given channel. In that case, the CCP can further identify mode I and mode II devices as sensing type 1, sensing type 2, sensing type 3, and sensing type 4. A sensing type 1 device, in addition to being able to operate as a Mode I or Mode II device (i.e. through the use of database information), can also operate as a sensing only device. It will be equipped with sensing HW/SW which allows it to monitor and detect both registered wireless microphone and DTT signals in a given TVWS channel. A sensing type 2 device may only detect DTT signals, whereas a sensing type 3 device may only detect wireless microphone. A sensing type 4 device is not capable of any kind of sensing. As shown in figure 34, Channel 3, 4 and 8 can be used by any class of device. However, channel 1 can only be used by sensing type 1 and sensing type 2 devices, and channel 2 can only be used by sensing type 1 and sensing type 3 devices.

The CCP assigns a set of channels to each AP or WS device based on sensing type and channel occupancy information from the geo-location database. Figure 34 illustrates, AP1 and AP2 being a sensing type 1 device, and so the CCP assigns vacant channels (e.g. 3, 4, 8) as well as channels which are occupied by DTT and WM according to the database (e.g. 1, 2, 5, 6, 7).

APs may use all the allocated channels in the DL, provided those channels are found to be unoccupied based on sensing results (as per the rules of a sensing only mode device), to communicate with the WS devices. However, for UL communication, WS devices may not use all the channels. Instead, WS devices may select the channels for UL use based on device sensing type. By selecting a channel for UL, the device may be selecting one several channels that a single AP is transmitting over (in the case of an AP supporting multiple channels simultaneously), or may be selecting the association with one AP over another (in the case that each AP uses only one channel).

EXAMPLE 2: In the figure 34 the sensing type device communicating with AP1, may use only Channel 1, channel 3 and channel 4, since it is only capable of sensing DTT.

In order to allow WS devices to make appropriate channel selection for UL communication, the AP may provide information about the sensing capability required for each channel. This information may be sent to the WS devices in various ways such as:

- Use of beacon signals.
- Broadcast the information on a control channels.

Figure 35 describes an example of procedure for communicating sensing capabilities through beacon signals in an 802.11 [i.29] system.

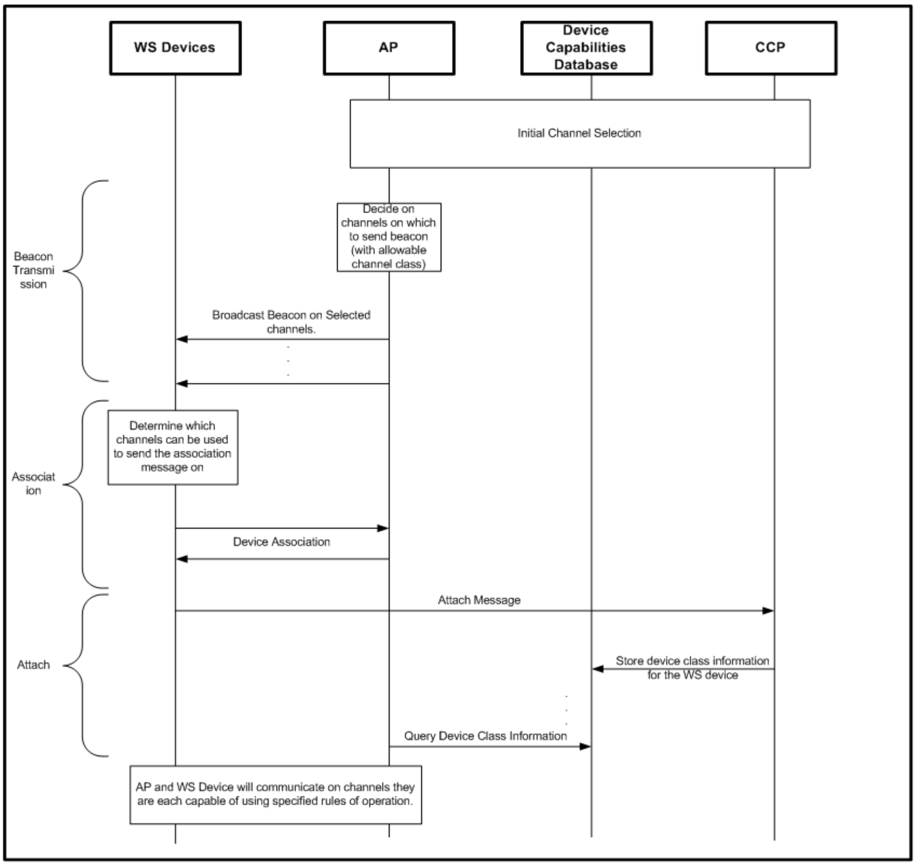


Figure 35: Example information flow for 802.11-based system

Beacon Transmission

In the information flow in figure 35, it is assumed that the beacon transmitted by the AP allows devices to determine which channels they can use by indicating the required sensing types for the associated channel. This is an enhancement to the current beacon in the IEEE 802.11 [i.29], as the beacon does not contain this information.

The CCP first allocates a single channel (the primary channel) to the AP to allow the AP to send beacons, and then provides additional channels as more devices join the network. The beacon sent out by an AP may contain a new field (in comparison to the beacon defined in IEEE 802.11 [i.29]) which contains an indication of the channel type associated with each channel used to send out the beacon. The channel type included with the beacon will indicate that this channel can be used by devices of certain sensing types (sensing type 1 to sensing type 4). A potential modified beacon in an 802.11 system containing an additional channel sensing type field is shown in figure 36.

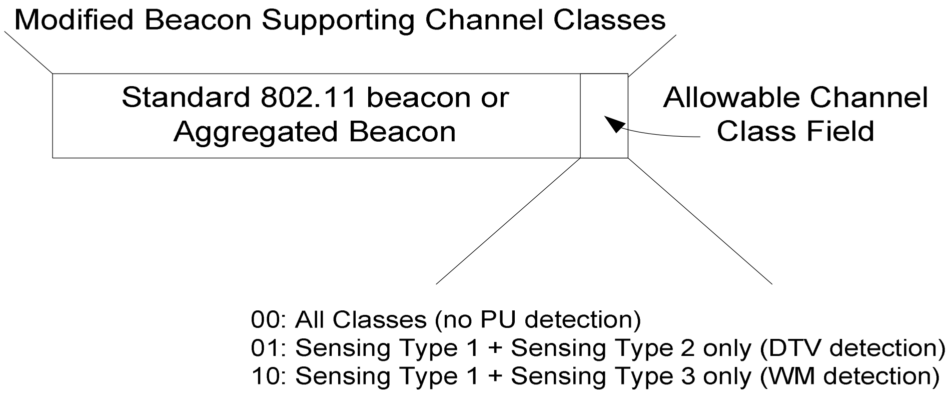


Figure 36: Modified Beacon Supporting Channel ClassesSensing Types

Beacons could be transmitted on all the channels that are used by an 802.11 AP. The AP may also choose to allow aggregation of transmission across multiple channels. It may allow for the transmission of a single beacon on one channel, where the beacon information on that channel will define the allowable channel sensing type for each of the channels in the aggregation set.

Association

A device that wishes to join an 802.11 network operating in TVWS will search for a beacon in any of the TVWS channels. Prior to sending any association messages to the AP, the device will verify the allowable channel sensing type field to determine if it is allowed to communicate on the channel(s) and send the association request.

EXAMPLE 3: If the beacon was transmitted on a free channel (all sensing types), the device can be associated immediately with the AP, regardless of its device sensing type.

On the other hand, if the channel type is a channel which was indicated to be reserved for DTT but determined by sensing at the device to be unoccupied, only devices of sensing type 1 and sensing type 2 can associate with the AP on this channel. Furthermore, the device can also determine the number of channels that it can use for transmission in the case of an aggregated channel scenario using the allowable channel sensing type for all the channels from the beacon. It may choose to send the association only on one of the channels (for example, the channel used to send the beacon), or it may be sent on multiple channels if possible.

Attach

Following association with the AP, the device will send an attach message, using either only the primary channel or the channels it is allowed to use based on its device sensing type and the sensing results at the device. The attach message may also contain the device sensing type as part of the device/sensing capabilities. The CCP can collect and store the device sensing type for each of the devices that have successfully attached. It will use this information in order to efficiently allocate channels for the system based on these device sensing types and on the occupancy information obtained from the TVWS database and the sensing at each device.

4.3.3 Using combined sensing and geo-location to enhance the protection/identification of incumbent services

4.3.3.1 Introduction

This clause provides a possible mechanism for enhancing the identification of incumbent services taking TV broadcast services as an example by using combined sensing and geo-location. The combined sensing/geo-location database mechanism, information flows and evaluation performance are introduced below. Chinese broadcast technologies i.e. DTMB and CMMB are used as TV broadcast technology examples, but this principle/concept can be generalized to other incumbent technologies such as wireless microphones.

4.3.3.2 Identify TV broadcast services

Some features of the TV signal, such as the reference signal, pilot sequence, the synchronization sequence, etc., could be exploited for TV signal detection. According to a cross-correlation or an autocorrelation approach, the detector can sense/detect the TV signal robustly compared to the blind detector. This kind of sensing is referred as feature sensing.

There are five global digital TV broadcasting standards including ATSC, DVB-T, ISDB, DTMB and CMMB. As an example, in China, two types of TV signals (DTMB for fixed receiver and CMMB for mobile receiver) are used. For DTMB, a major challenge in the design of the feature sensing is the fact that DTMB specifies three different modes of operation shown in figure 37, each with a single- or multi-carrier option for the data payload. These modes mainly differ in the shape of the frame header which has a significant impact on the conditioning/performance of the sensing detector. This header can be used for synchronization and channel estimation and, hence, it is ideally suited for the detection of the presence of the signal at the receiver input. For CMMB, two types of system bandwidths are supported. All pilot symbols are scrambled by PN sequence and eight initial states are supported. These pilot symbols are unique for CMMB and suited for the detection of CMMB signals.

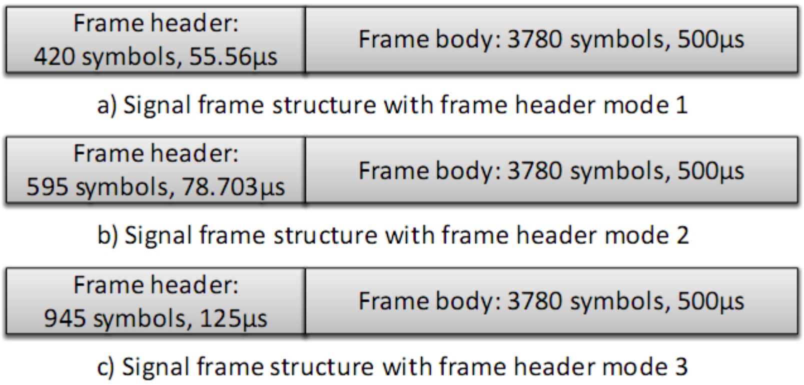


Figure 37: DTMB signal frame structure

There are at least three signal frame structures for DTMB (see figure 37) and eight pilot symbol structures for CMMB. For CMMB, the pilot symbols are repeated every 53 OFDM symbols, so at least 53 OFDM symbols would be needed to detect a CMMB signal. However, if the geo-location database can provide the TV signal's basic configuration such as frame structure or pilot symbol information, the WSD will know prior sensing what are the coding schemes of the corresponding TV channels and consequently it can reduce sensing time and/or improve sensing accuracy.

4.3.3.3 Geo-location database aided feature sensing description

In combined sensing and geo-location database method, due to different TV system configurations, the TV system registers its configuration information in the database as a first step. For example:

- If TV broadcasting service adopts DTMB, the configuration information should include the mode of frame header.
- If TV broadcasting service is using CMMB, the configuration information should include the mode of pilots.

The TV configuration information update in the geo-location database can be done whenever the information is changed.

The database may provide the information to WSDs either as a push or upon WSD request. The WSDs select appropriate sensing algorithm accordingly to perform sensing to enhance the identification of incumbent users.

4.3.3.4 Information Flow Among Relevant Entities

An example of the information flow between geo-location database and WSDs is presented in figure 38.

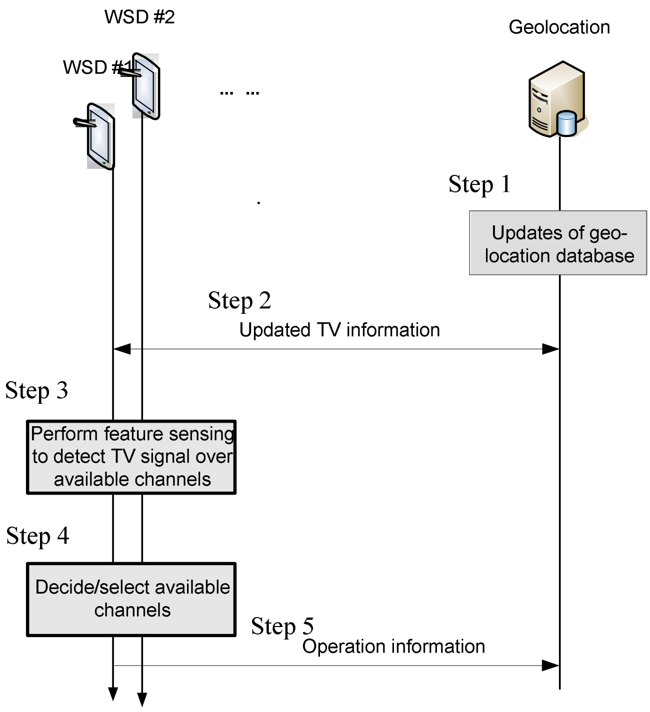


Figure 38: Information flow between geo-location database and WSDs

Step 1: TV configuration information is saved in the geo-location database, including the types of TV system, mode of frame header, pilot, etc. The information is updated in the geo-location database when TV system parameters are changed.

Step 2: Geo-location database knows the location of WSDs and pushes corresponding TV system information to WSDs, including the category of TV systems and configuration information such as the mode of frame headers or the mode of pilots. Alternatively WSDs connect to the geo-location database to request the available channels and geo-location database provides available channels and corresponding TV configuration information to WSDs. The requested information is only valid for a specified time. WSD should re-request information after the specified time if it wishes to operate on a channel or use the TV configuration information for spectrum sensing.

Step 3: WSDs select appropriate sensing algorithm according to the TV configuration information retrieved in step 2. It may perform sensing to enhance the identification of incumbent users.

Step 4: WSDs decide and select an operation channel from the available channels, which the geo-locaton database provides, using sensing results.

Step 5: WSDs may register their operation information to geo-location database.

4.3.3.5 Performance evaluation on geo-location database aided sensing design

In clauses 4.3.3.3 and 4.3.3.4, the use of sensing in parallel with geo-location database access is described and this can lead to faster and more reliable identification of incumbent services when compared to sensing only. This clause provides a performance evaluation of geo-location database aided sensing design and demonstrates its advantage. The performance of Chinese broadcast technology DTMB is used as an example for evaluation, and this performance can also be generalized to other broadcast technologies such as CMMB, DVB, etc.

In order to assess the possible benefits of this scheme, the performance of conventional sensing approaches in TV white space will be compared to this combined approach.

Firstly, the combined approach is shown to speed up the identification of incumbent services, where it decreases the time needed to identify the incumbent when compared with the sensing only approach.

As mentioned above, if WSDs cannot obtain any information about the incumbent configuration information from the geo-location database, they might execute all supported sensing algorithms before detecting an incumbent. Here it is assumed that an algorithm enables detecting a specific incumbent, and the WSDs may perform sensing algorithms serially until they detect the incumbent. If the WSDs get the information of the TV configuration from the database, they may perform sensing only with the appropriate algorithm. Also, if they do not support the appropriate sensing algorithm to detect the incumbent, they do not need to perform sensing at all.

If X ms is assumed as the average time spent on performing sensing with one algorithm and Y is the number of sensing algorithm types that the WSD may need to apply, then according to binomial distribution random probability, the average time to detect an incumbent by WSD is $T = (Y+1) * \frac{Y}{2} * P * X$, where $P = 1/Y$ is the probability of detecting one incumbent with one algorithm. After obtaining TV configuration information, the WSD can only execute one algorithm which supports the detection of the TV system, and thus the WSD only needs X ms to detect the incumbent TV system.

Below, X is assumed as 20 ms. According to [i.21] 20 ms is considered to be enough to detect. The number of sensing algorithms changes from 1 to 10. The average sensing time with the sensing only approach is shown in figure 39. The geo-location database aided sensing design can drastically decease the time for sensing, and the sensing time with this combined approach is 20 ms.

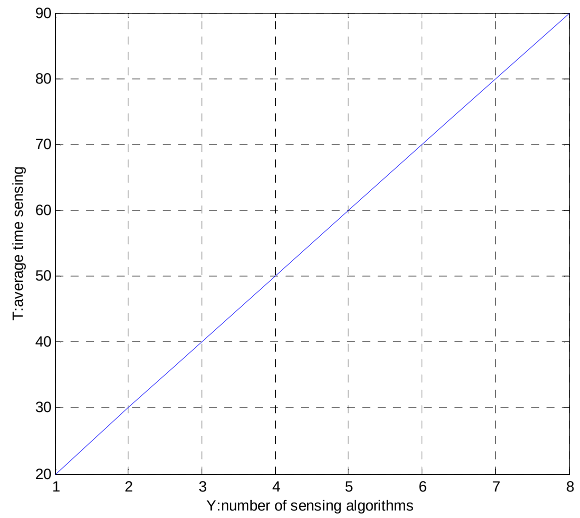


Figure 39: Performance of the average sensing time with sensing only approach

Secondly, it is shown that the combined approach enhances the identification of incumbent services since it increases the sensing reliability when compared with sensing only approach using non-feature-based sensing. In the non-feature-based sensing approach the WSD does not know the incumbent signal feature information, such as pilot, synchronization sequence, etc. Energy detection is one of the commonly used non-feature-based sensing algorithms and is compared with the combined approach below. Obviously, the non-feature-based detection has some drawbacks, e.g. energy detection does not enable identifying the type of the interference.

If the WSD cannot obtain any information about incumbent, a non-feature-based sensing algorithm may be adopted for sensing. The performance of the energy detection algorithm is depicted in figure 40 for the false-alarm probabilities 0,1 and 0,01 respectively within white noise only. Here, the false-negative probability (i.e. miss-detection probability) of three modes of DTMB signal is plotted versus SNR. Mode1 to Mode3 represent three signal frame structures in DTMB respectively, and the detail of signal frame structures have been presented in figure 37 in clause 4.3.3.2, P_{fa} is the false-alarm probability, and P_{md} is the miss-detection probability. The performance has been simulated with DVB channel models for fixed reception in [i.20]. It is difficult to sense for portable equipment, because it will increase the cost, complexity and energy consumption of portable equipment. Thus in this scheme it only considers sensing for base station. In other words, the evaluation only considers fixed reception channel models (Rice fading) here and does not consider channel model for portable reception (Raleigh fading). The fixed reception channel consists of 21 paths and is also used for DTMB. Since the power in LOS path accounts for 91 % of whole paths power, then performance is a little worse than that in AWGN channel model. All detailed simulation configurations for figures 40 and 41 are listed in table 11.

Table 11: Simulation parameters

Category	Configuration
TV signal type	DTMB Mode1, Mode2 and Mode3
Frame header	PN420, PN595 and PN945
Frame body	3 780 symbols
Sensing algorithm	Energy sensing Cross-correlation sensing
Noise uncertainty	1 dB
Sensing time	3 ms
False-alarm probability	0,1, 0,01
Channel model	21 Paths channel (DVB fixed reception)

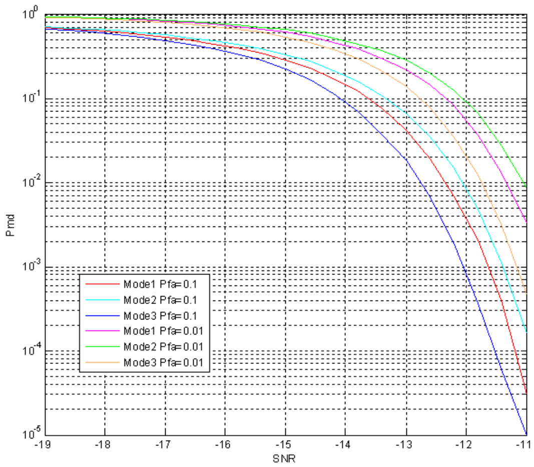


Figure 40: Performance of the energy sensing algorithm based on DTMB signals

The simulation results above show that the performance of mode3 is the best and the performance of mode2 is the worst. Because the power of frame header is two times that of the frame body in mode1 and mode3, while the power of the frame header is the same as that of frame body in mode2. In the simulation, it is assumed that the powers of frame bodies in all modes are the same. Therefore the energies of frames in mode1 and mode3 are larger than the energy in mode2, and the performances are better than that in mode2. Moreover, the frame in mode3 has longer frame header compared with mode1, therefore the frame in mode3 has larger energy than mode2, and the performance of mode3 is better than that of mode1.

However, when WSDs obtain the TV configuration information from the geo-location database, they can sense/detect the features of the TV signals, if they support the feature detection of the TV signal. The performance of the cross-correlation sensing algorithm based on DTMB signals is depicted in figure 41 for the false-alarm probabilities 0,1 and 0,01 respectively. In both simulations, the noise uncertainty which impacts the simulation threshold follows Gaussian distribution and the standard deviation is 1 dB and the noise power affected by noise uncertainty is assumed to be considered at WSDs. The performance has been also simulated with DVB channel models for fixed reception in [i.20], and the sensing time in energy sensing and cross-correlation sensing is 3 ms.

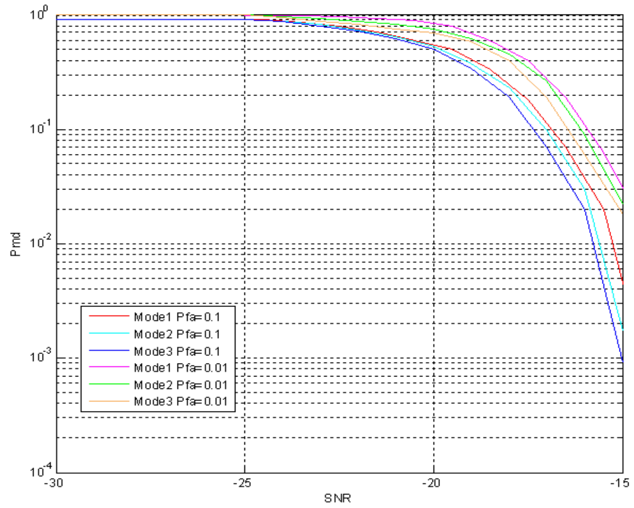


Figure 41: Performance of the cross-correlation sensing algorithm based on DTMB signals

The performances of the cross-correlation sensing algorithm for DTMB are depicted in figure 41. It can easily be shown that the performance of mode3 is better than that of mode2 and mode 1. Because the frame header in mode3 consists of the longest PN sequences, and the frame header in mode 1 consists of the shortest PN sequences, where the PN sequences are used for cross-correlation sensing, which reflects the performance of cross-correlation sensing algorithm.

Given the comparison between figures 40 and 41, WSDs can sense lower TV SNR with cross-correlation, so cross-correlation can provide more reliable identification of incumbent and the performance of geo-location database aided sensing is better than that in non-feature-based sensing.

4.3.3.6 Conclusions

In this clause a geo-location database aided sensing technology was presented and compared with the sensing only scheme. The results show that the geo-location aided sensing method can provide more accurate and rapid identification of incumbent services when compared to standalone sensing approach. If the WSD gets information of the TV system configuration from the geo-location database, it can optimize the sensing e.g. by selecting the detection algorithm accordingly. This method can be applied to both channel selection flow and channel switch flow in clause 4.3.2.2 as well.

4.4 Combined Interference Monitoring and Geo-location Database Design

4.4.1 Introduction

Geo-location database approaches using radio propagation estimation have been regarded as practical incumbent protection methods. However, propagation models inevitably include estimation error of path loss in actual radio environments, resulting in estimation error of carrier to interference ratio (CIR) of the incumbent receivers. To improve the accuracy of CIR estimation, Interference Monitoring can be applied. It enables estimating CIR by combining measurements around the incumbent receiver and propagation estimation. Owing to the Interference Monitoring, the geo-location database can utilize the improved CIR estimate to recalculate new allowable transmit power. Thus the combined Interference Monitoring and geo-location database can protect the incumbent system from harmful interference while expanding white space opportunities.

4.4.2 System Model

This clause mainly focuses on a use case in which a cellular system applies cognitive radio technologies to manage the ever-growing mobile traffic. A similar use case for TD-LTE is described in TR 102 907 [i.22]. In this scenario, the cellular system as the CRS will extend its system bandwidth by using white space in addition to licensed bands for regular operation. The extension of the bandwidth will be on the basis of requests from the WSD such as the Base Station (BS). In this clause, it is assumed that the extended band is used only for downlink transmission. Although the cellular system is taken here as an example use case, the described Interference Monitoring concept can also be applied to other systems such as WLAN and WRAN.

The concept of the cellular system with extended band is shown in figure 42. For the incumbent system, a broadcast system such as digital TV is assumed. In this figure, only two key BSs are shown for a simplified explanation of Interference Monitoring concept: one is located far from the service area of the incumbent system; and the other is located in or near the service area. The former BS runs opportunistic transmission using TVWS band as an additional operation band as allowed by the geo-location database. The latter BS has spectrum sensing capability and acts as a spectrum sensor which is used for the Interference Monitoring. Dedicated spectrum sensors might be also used for the same purpose.

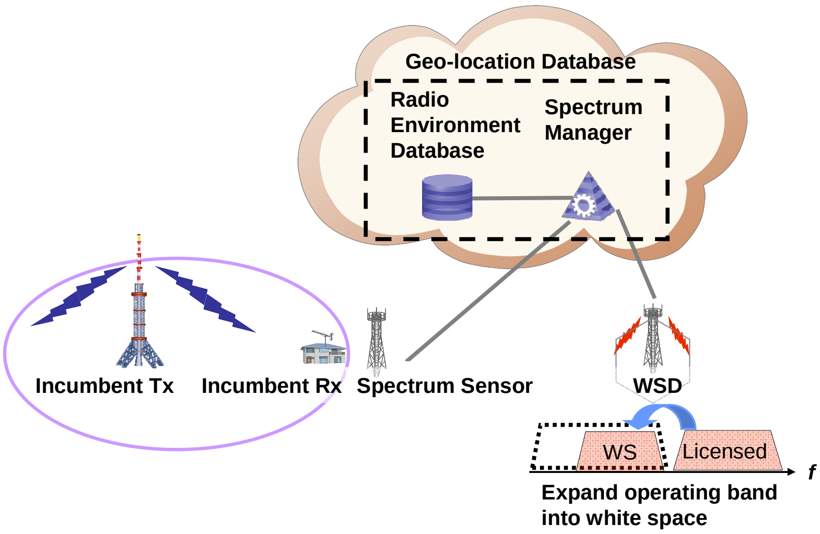


Figure 42: The system model of cellular system with extended band

Geo-location database can be split into two functional entities: spectrum manager and radio environment database. The spectrum manager calculates the allowable transmit power of the WSD that has requested use of white space spectrum. The power is basically determined so that the CIR at the incumbent receiver (Rx) based on the propagation estimation can be kept at a required level. Since the location of real incumbent Rx is unknown, the spectrum manager assumes a location where the real incumbent Rx may reside. We refer this location to as the potential incumbent Rx. To realize incumbent protection in the service area, the worst-case incumbent Rx is used for the calculation of the power. Such receiver is typically at the service area edge and has the lowest CIR value. In this way, the spectrum manager protects incumbent system using the propagation estimation.

The estimated path loss always includes estimation error due to the mismatch of the propagation model and shadowing. Therefore, the estimated CIR of the potential incumbent Rx obtained by the propagation estimation also includes estimation error. To keep the required CIR (CIR_{req}) at the potential incumbent Rx, the spectrum manager limits the allowable transmit power by taking into account the margin for the possible propagation estimation error. Such margin is characterized as a standard deviation of CIR estimation error multiplied by the Gaussian confidence factor (q) for a protection probability (1,645 for 95 %). The CIR can be kept at the required value in the case of the interference from one WSD. To take into account the aggregated interference from the multiple WSDs, multiple interference margin (MI) is also considered in the allowable transmit power.

We explain the calculation of the allowable transmit power below. This is to show the difference between the power in this clause and that in [i.3]. In the following, dB is used as a unit for the power. The allowable transmit power calculated in the above process is given by:

$$P_I^{\mathrm{PE}} = (P_C + G_C^{\mathrm{Tx}} - \hat{L}_{C,0} + G_{C,0}^{\mathrm{Rx}}) - (G_I^{\mathrm{Tx}} - \hat{L}_{I,0} + G_{I,0}^{\mathrm{Rx}}) - \mathrm{CIR}_{\mathrm{req}} - q\sqrt{2}\sigma_L - \mathrm{MI} \quad (15)$$

where P_I^{PE} and P_C are the allowable transmit power of the WSD based on the propagation estimation and the transmit power of the incumbent Tx. G_C^{Tx}, $G_{C,0}^{\mathrm{Rx}}$, G_I^{Tx}, and $G_{I,0}^{\mathrm{Rx}}$ are the antenna gains of the incumbent Tx, of the potential incumbent Rx toward the incumbent Tx, of the WSD, and of the incumbent Rx toward the WSD, respectively. In addition, $\hat{L}_{C,0}$ and $\hat{L}_{I,0}$ are the estimated path loss between the incumbent Tx and the potential incumbent Rx and that between the WSD and the potential incumbent Rx. The estimation error of the path loss between the WSD and the potential incumbent Rx and that between the incumbent Tx and the potential incumbent Rx are assumed to have the same distribution with mean of 0 and the standard deviation of σ_L. Thus, the standard deviation of CIR estimation error is given by $\sqrt{\sigma_L^2 + \sigma_L^2} = \sqrt{2}\sigma_L$. Also the corresponding margin is represented by $q\sqrt{2}\sigma_L$ in (15). Both the allowable transmit power in (15) and that in [i.3] consider the same multiple interference margin. The difference between (15) and the power in [i.3] is how to design the margin for radio propagation estimation. The margin in (15) is based on the standard deviation of the propagation estimation errors, which will be caused by both shadowing and other error factors such as the mismatch of the propagation model. On the other hand, the margin for the shadowing and that for the other factors are separately considered in the allowable transmit power in [i.3]. In [i.3], the margin for the shadowing is expressed as $q\sqrt{\sigma_{\mathrm{BS}}^2 + \sigma_{\mathrm{WSD}}^2}$, where σ_{BS} and σ_{WSD} are the standard deviation of shadowing of the incumbent signal for broadcasting service and that of the interference signal from WSD. Other factors for the propagation estimation error can be considered in the safety margin which mainly aims to provide protection against existing co-primary interference. In order to explicitly treat the CIR estimation errors caused by the radio propagation estimation, this clause adopts the margin in (15) and aims to reduce it by improving the CIR estimation accuracy. Although the expression is different from the margins in [i.3], the Interference Monitoring detailed below can also reduce the safety margin in [i.3] as well.

The radio environment database stores information on location, height, transmit power, and antenna gain of the incumbent Tx. The receiver antenna gain of typical incumbent Rx is also stored. In addition, it also stores information on location, height, and transmitter antenna gain of the registered WSD in the database. The path loss between the WSD and the incumbent Rx is calculated based on a propagation model, and is also stored in the database. The information is used for the calculation of the allowable transmit power by the spectrum manager.

4.4.3 Interference Monitoring

4.4.3.1 Concept

The concept of the Interference Monitoring is shown in figure 43. First, the spectrum manager calculates the allowable transmit power of WSD based on the propagation estimation and provides the information to the WSD. The power is limited by including both the margin for propagation estimation error and that for multiple interferences so that CIR of the incumbent Rx can be kept at the required level. Then the WSD starts transmission at power not exceeding the provided one. The Interference Monitoring is performed as follows: both the interference power from the WSD and the incumbent signal power are actually measured at spectrum sensors which are located near the worst-case potential incumbent Rx at the edge of incumbent service area. Using the measurement results, the CIR of the potential incumbent Rx estimated by the propagation model is compensated. In this way, the actual measurements are effectively used to improve the CIR estimation accuracy. Then the geo-location database can utilize the resultant CIR estimate to recalculate new allowable transmit power. Thus the combined Interference Monitoring and geo-location database can protect the incumbent system from harmful interference while expanding white space opportunities.

Note that the purpose of the Interference Monitoring is different from that of the incumbent signal detection by spectrum sensing. The spectrum sensing is basically for detecting incumbent signals to determine if the incumbent transmitters are operating around the WSD. On the other hand, the Interference Monitoring determines how much interference is actually caused to the potential incumbent Rx.

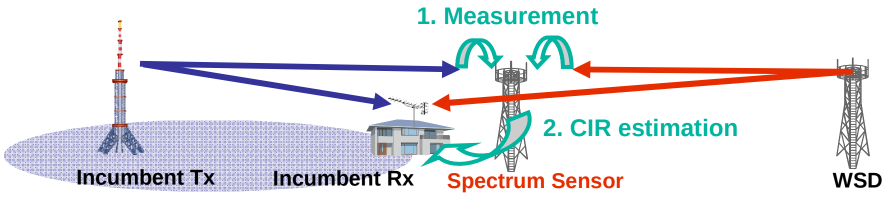


Figure 43: The concept of Interference Monitoring

4.4.3.2 General Operations

4.4.3.2.1 Procedures

An example of procedure for the Interference Monitoring is shown in figure 44. The spectrum manager of the geo-location database calculates the allowable transmit power of the WSD that requests use of white space spectrum. Such power is conservatively set to keep the CIR of the potential incumbent Rx at the required level. To calculate the power, the spectrum manager gets appropriate information from the radio environment database to estimate the CIR of the potential incumbent Rx, such as the transmit power, transmit antenna gain, path loss, and typical receiver antenna gain of the incumbent system, etc. Information on the WSD is also needed for the calculation, such as the transmit antenna gain of the WSD and path loss between the WSD and the potential incumbent Rx. The transmit antenna gain of the WSD is provided by the WSD, whereas the path loss is estimated based on the propagation model using the location and height information of the WSD. The spectrum manager notifies the WSD of a list of available TV channels and the allowable transmit power for each channel. The WSD selects a channel to use based on the list and transmit power not exceeding the allowable power. Then WSD starts its operation.

Once the WSD starts operating in the TV white space channel, it initiates the Interference Monitoring. In the request for the Interference Monitoring, the WSD may send the information on the operating channel and the transmit power to the spectrum manager. Such information enables to estimate the interference power at the potential incumbent Rx based on propagation estimation which can be effectively combined with the interference power measured at sensor. However, it is also possible to estimate the interference power at the potential incumbent Rx using only the measured interference power. In this case, such information is not necessary to be stored.

First, the spectrum sensor measures the interference signal and incumbent signal. Next, the spectrum manager estimates the CIR at the worst-case potential incumbent receiver based on these measurements and propagation estimation. Finally, the spectrum manager recalculates the allowable transmit power of the WSD using the resultant CIR. The WSD updates its transmission parameters such as the transmit power or channel to use according to the recalculated allowable transmit power notified by the spectrum manager. If the transmit power and channel of the WSD are used to estimate the interference power, WSD sends such information to the radio environment database. Thus the incumbent system can be protected during these processes.

In the case that the spectrum manager does not know the actual transmit power and operating channel of the WSD, it may be difficult to adjust the allowable transmit power of each WSD due to limited information. But, it is possible to adjust the allowable transmit power using a same value for all related WSDs. For example, the spectrum manager instruct the WSDs to decrease their allowable transmit power by x dB based on the interference estimate.

In another example procedure the spectrum manager may configure the interference monitoring in spectrum sensors and regularly receive measurement information from them. If the spectrum manager has up-to-date measurement information available in a geo-location area, it can use the information when estimating allowable transmit power to any WSD that requests the use of white space spectrum in that geo-location area.

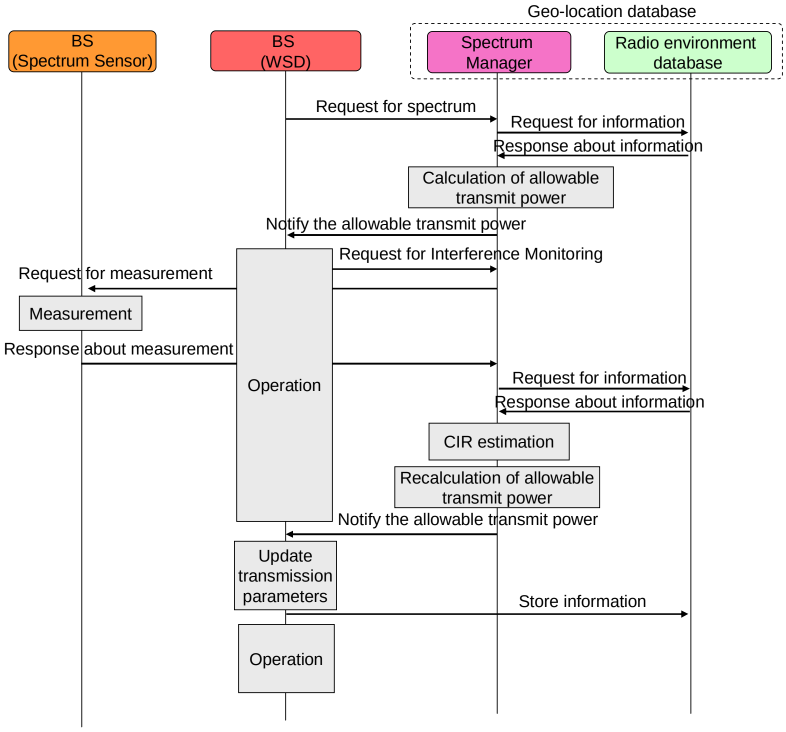


Figure 44: Procedure of the Interference Monitoring

4.4.3.2.2 CIR Estimation in Single Sensor Case

This clause describes the Interference Monitoring with a single spectrum sensor. A diagram of the Interference Monitoring with a single spectrum sensor is shown in figure 45. The spectrum sensor indexed by k measures the received power of both the interference signals (I_k) and the incumbent signals (C_k) at its location, where the distance between the worst-case potential incumbent Rx and the spectrum sensor is represented as $d_{0,k}$. These measurements are used to estimate interference signals (I_0) and the incumbent signals (C_0) at the potential incumbent Rx indexed by 0, and then to estimate CIR at the potential incumbent Rx.

Basically, these measurements are performed on the operating channel of the incumbent system and that of the WSD when the incumbent Tx is transmitting. In this case, the sensor needs to have ability to measure the power of the incumbent signals (e.g. feature detection). In addition, two types of the measurement of the interference signal can be considered: individual interference measurement and aggregated interference measurement. The former one is to measure interference signal of each WSD. This measurement is used to compensate the interference signal of each WSD. It requires specific feature of each WSD to separate the signals from those of other WSDs which use the same radio technology. Example of such feature is WSD-specific pilot signals. Other WSD-specific feature can also be used. To utilize these features, the sensor needs to know some information on the features. On the other hand, the latter one does not require such information, because the aggregated interference can be measured by subtracting the incumbent signal power from the total received power in the operating channel of the WSD. The aggregated interference measured at the sensor can be used to estimate the aggregated interference at the potential incumbent Rx. We take individual interference measurement in this clause. Thus I_k is assumed to be the interference signal from one WSD.

First, the WSD transmits its signal with the power not exceeding the allowable transmit power based on the propagation estimation. The estimates of the received signal power, $\hat{C}_0^{\mathrm{PE}}$ and $\hat{I}_0^{\mathrm{PE}}$, at the potential incumbent Rx based on the propagation estimation can be calculated by using the transmit power, transmit antenna gain, the estimated path loss, and received antenna gain. These estimates are compensated by using $\tilde{I}_k$ and $\tilde{C}_k$, which represent measured I_k and C_k. In the Interference Monitoring, $\hat{C}_0^{\mathrm{PE}}$ and $\hat{I}_0^{\mathrm{PE}}$ are separately compensated as:

$$\hat{C}_0^{\mathrm{IM}} = \hat{C}_0^{\mathrm{PE}} + w_{C,k}(\tilde{C}_k - \hat{C}_k^{\mathrm{PE}}) \tag{16}$$

$$\hat{I}_0^{\mathrm{IM}} = \hat{I}_0^{\mathrm{PE}} + w_{I,k}(\tilde{I}_k - \hat{I}_k^{\mathrm{PE}}) \tag{17}$$

where $\hat{C}_0^{\mathrm{IM}}$ and $\hat{I}_0^{\mathrm{IM}}$ are respectively the compensated estimates of the incumbent signal power and the interference signal power from the WSD at the potential incumbent Rx. In addition, $\hat{C}_k^{\mathrm{PE}}$ and $\hat{I}_k^{\mathrm{PE}}$ are the estimates of the incumbent signal power and the interference signal power at the spectrum sensor, respectively. The compensated CIR at the incumbent Rx is obtained by $(\hat{C}_0^{\mathrm{IM}} - \hat{I}_0^{\mathrm{IM}})$. The weights, $w_{C,k}$ and $w_{I,k}$, are determined so that they can minimize the mean square error of the compensated CIR.

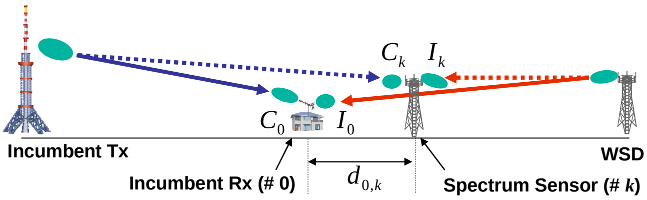


Figure 45: Interference Monitoring for single sensor case and single WSD causing interference

The reliability of the compensation using those measurements depends on the correlation between path-loss estimation error at the incumbent Rx and that at the spectrum sensor. When the correlation is high, the measurements at the spectrum sensor are helpful for compensating the CIR estimate. This correlation is assumed to be represented by the exponentially-decaying function of the distance between the potential incumbent Rx and the spectrum sensor. This function is characterized by the decorrelation distance at which the correlation becomes 0,5. In addition, the reliability also depends on possible measurement errors at the spectrum sensor. Therefore, the allowable transmit power will be recalculated considering a margin for these influences.

4.4.3.2.3 CIR Estimation in Multiple Sensor Case

When multiple spectrum sensors are available, the Interference Monitoring technique can be extended as cooperative manner. A diagram of the Cooperative Interference Monitoring technique is shown in figure 46. In the figure, there are two spectrum sensors (k and k'), which measure the received power of both the incumbent signals and the interference signals. As already explained, the path-loss estimation error at the incumbent Rx and that at the spectrum sensors are correlated with correlations of $\rho_{0,k}$ and $\rho_{0,k'}$. Moreover, the estimation errors at the spectrum sensors are also correlated with correlation of $\rho_{k,k'}$ according to the distance between the spectrum sensors. When the spectrum sensors are far from each other, measurement results of them have low correlation, and thus the gain of the multiple spectrum sensors for CIR compensation is high because of the spatial diversity. Meanwhile, when the spectrum sensors are close to each other, the measurement results of them are highly correlated, and the gain of multiple spectrum sensors for CIR compensation is low. In Cooperative Interference Monitoring, this diversity gain contributes to the CIR compensation.

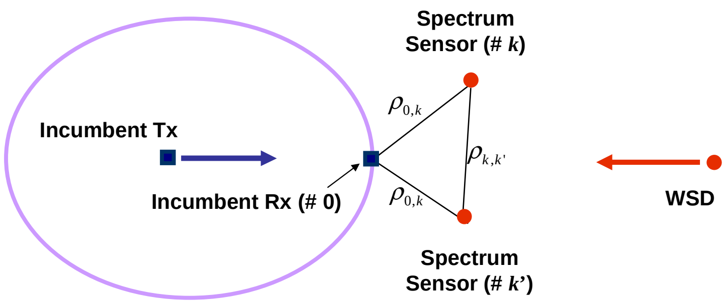


Figure 46: Cooperative Interference Monitoring for single WSD causing interference

Here, the number of monitoring nodes is assumed as K. Following the compensation of the single monitoring node case, the estimates of the signal power at the potential incumbent Rx based on the propagation estimation are compensated as:

$$\hat{C}_0^{\mathrm{IM}} = \hat{C}_0^{\mathrm{PE}} + \sum_{k=1}^{K} w_{C,k} (\tilde{C}_k - \hat{C}_k^{\mathrm{PE}}) \tag{18}$$

$$\hat{I}_0^{\mathrm{IM}} = \hat{I}_0^{\mathrm{PE}} + \sum_{k=1}^{K} w_{I,k} (\tilde{I}_k - \hat{I}_k^{\mathrm{PE}}) \tag{19}$$

The compensated CIR at the potential incumbent Rx is also obtained by $(\hat{C}_0^{\mathrm{IM}} - \hat{I}_0^{\mathrm{IM}})$. The optimal weights can be obtained so that they can minimize the mean square error of the compensated CIR.

4.4.3.2.4 Allowable Transmit Power Calculation

The allowable transmit power is recalculated based on the compensated CIR by the Interference Monitoring. In the recalculation, difference between the compensated CIR and $\mathrm{CIR}_{\mathrm{req}}$ is added to the current transmit power of P_I^{PE} for adjustment. In the recalculation, the margin also should be considered on the basis of the standard deviation of the CIR estimation error of the Interference Monitoring (σ_{IM}) to keep $\mathrm{CIR}_{\mathrm{req}}$ with a certain protection probability. Thus, the allowable transmit power of the Interference Monitoring, P_I^{IM}, is obtained by:

$$P_I^{\mathrm{IM}} = P_I^{\mathrm{PE}} + (\hat{C}_0^{\mathrm{IM}} - \hat{I}_0^{\mathrm{IM}}) - \mathrm{CIR}_{\mathrm{req}} - q\sigma_{\mathrm{IM}} - \mathrm{MI} \tag{20}$$

Compared to the standard deviation of the CIR estimation error based on the propagation estimation, σ_{IM} can be a smaller value owing to the accuracy improvement by the actual measurements. Therefore, the Interference Monitoring can lead to increase the allowable transmit power by reducing the margin.

4.4.4 Performance of Interference Monitoring

Analytical evaluations are presented in this clause to compare the allowable transmit power by the Interference Monitoring and the path-loss estimation. For convenience, effective isotropic radiated power (EIRP) is used in the following evaluation instead of using both the allowable transmit power and the transmit antenna gain for incumbent Tx and WSD. In the evaluation, we assumed one WSD is CRS. The allowable EIRP of the WSD is calculated so that it could keep the required CIR (21 dB) [i.3] of the incumbent Rx to be protected with the protection probability of 95 %. Furthermore, the safety margin of 20 dB was added to the power not for the propagation estimation error but for the existing co-primary interference. Such EIRP is averaged according to the distribution of the estimation error of the path loss. In addition, the worst-case incumbent Rx is located in a cell of the spectrum sensor with a uniform distribution. Then, the Complementary Cumulative Distribution Function (CCDF) of the average allowable EIRP is evaluated.

As for the propagation model, Recommendation ITU-R P.1546-4 [i.6] model is used. To evaluate the site-generic model and the site-specific model, two sets of the standard deviation of the path loss estimation error and the decorrelation distance are used. The standard deviation of the estimation error of the site-generic model is set to 15,8 dB [i.13] and the decorrelation distance of the estimation error is set to 288 m. On the other hand, the site-specific model is assumed as the standard deviation of 9,3 dB [i.13] and the decorrelation distance of 150 m.

Digital Terrestrial Television (DTT) with outdoor reception was assumed as an incumbent system. The antenna height and EIRP of the incumbent Tx were set to 100 m and 72,15 dBm [i.3]. The antenna height of the incumbent Rx is set to 10 m [i.3]. We used a receiver antenna gain with front to back ratio of 16 dB. The main beam of the antenna with the gain of 9,15 dBi [i.3] is directed at the incumbent Tx, whereas the opposite side with the gain of -6,85 dBi is directed at the WSD. The service area of the incumbent system was determined so that Carrier to Noise Ratio (CNR) of the incumbent Rx could satisfy 21 dB with a probability of 70 %. Then, the service area based on the Recommendation ITU-R P.1546-4 [i.6] model was 44,7 km. The target incumbent Rx to keep the required CIR was set to the edge of this service area, which is the nearest from the WSD.

The height of the BS of a cellular system was used for the WSD. The spectrum sensors are also assumed to be installed at BSs of the cellular system, where inter site distance (ISD) is 500 m. The standard deviation of the measurement error of the interference signals and that of the incumbent signals are set to 4,6 dB and 0,1 dB, respectively. Since the received power of the incumbent signal at the spectrum sensors was much higher than that of the interference signal, the standard deviation for the incumbent signal was set to be relatively low.

The separation between the incumbent Rx and the WSD is set to 30 km. Other parameters are set as listed in table 12.

Figure 47 shows the CCDF of the average allowable EIRP of the Interference Monitoring with a single sensor and four sensors. Compared with path-loss estimation by the site-generic model, the Interference Monitoring with a single sensor achieves an 8 dB increase in the average allowable EIRP at CCDF = 50 %. Cooperative Interference Monitoring with four sensors achieves 3 dB of additional increase by spatial diversity. Meanwhile, the gain becomes relatively small in the case of the site-specific model. Since the estimation accuracy of the path loss in this case is improved in comparison with the site-generic model, the gain obtained by the Interference Monitoring becomes low. Furthermore, the short decorrelation distance of the site-specific model further lowers the gain, because the correlation of the path loss estimation errors between the incumbent Rx and the spectrum sensor becomes low. Nevertheless, the Interference Monitoring with a single node and four nodes achieves about 2 dB improvements.

Table 12: Evaluation conditions

Category	Parameters	Value
Propagation environment	Propagation model	Recommendation ITU-R P.1546-4 [i.6]
	Center frequency	600 MHz
	Reference height of buildings	10 m
	Standard deviation of path loss estimation error	15,8, 9,3 dB
	Decorrelation distance	288, 150 m
Incumbent Tx (DTT transmitter)	Antenna height	100 m
	EIRP	72,15 dBm
Incumbent Rx (DTT receiver)	Antenna height	10 m
	Antenna gain toward incumbent Tx	9,15 dBi
	Antenna gain toward WSD	-6,85 dBi
	Required CNR	21 dB
	Noise power	-98,17 dBm
Interference requirement	Safety margin	20 dB
	Required CIR	21 dB
WSD	Antenna height	32 m
Spectrum sensor	Antenna height	32 m
	Standard deviation of measurement error for incumbent signal	0,1 dB
	Standard deviation of measurement error for interference signal	4,6 dB

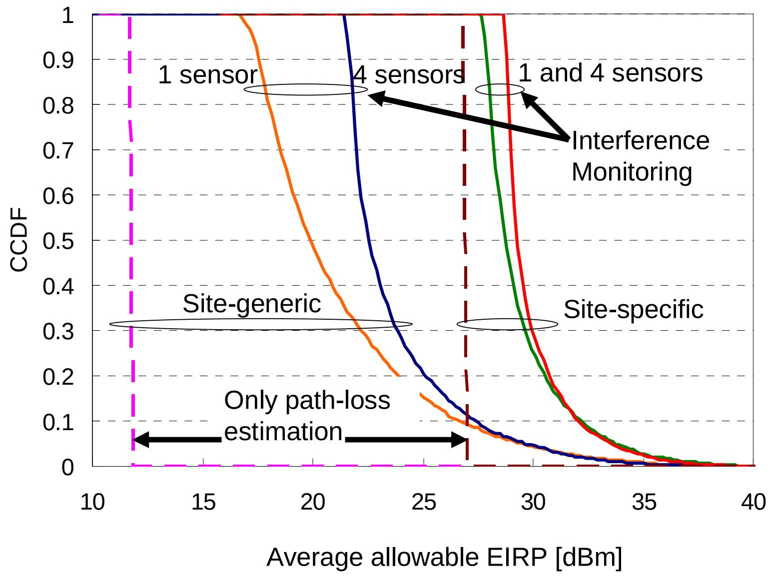


Figure 47: CCDF of the average allowable EIRP

4.4.5 Conclusions

Interference Monitoring aims to improve accuracy of estimated CIR of the incumbent receiver and thus to reduce the required margin of the allowable transmit power. Key point of Interference Monitoring is that actual measurements of both interference signals and incumbent signals are performed. Using these measurement results, the estimated CIR by the radio propagation model can be compensated. Furthermore, Cooperative Interference Monitoring can be applied for utilizing spatial diversity when multiple spectrum sensors are available. Results from the performance evaluations show that Interference Monitoring can improve the estimation accuracy of CIR and thus can significantly increase the allowable transmit power. Compared with geo-location database approach based on path-loss estimation by the site-generic model, the Interference Monitoring with a single sensor achieved an 8 dB increase in the average allowable EIRP at CCDF = 50 %. Moreover, cooperation of four sensors achieved 3 dB of additional increase by spatial diversity. The drawback of the Interference Monitoring compared to the geo-location database approach is that it requires deployed sensors. Although the cost will be higher due to this, using BS as a sensor will alleviate the problem.

4.5 Spectral Pre-coding

4.5.1 Introduction

Along with the obvious requirements on out-of-band emission (72,8 dB is required by FCC [i.1]), next-generation cognitive radio systems are also likely to require transceivers to adapt the signal spectral characteristics to its neighbouring radio. In particular, CRS transmitters are likely to be based on system architectures that require high levels of frequency isolation and frequency flexibility.

When multi-carrier modulation for large band operation such as TVWS is mentioned, then spectral agility characteristics of CRS transceivers are questioned. Even if sub-carriers in the multiplexing can be switched on and off, and transparent adaptation seems feasible [i.7], out-of-band power emission of OFDM is a reported problem. The relatively slow power spectral band-edge decay of OFDM signals has been a subject of concern ever since their first constructions. Today's OFDM standards and systems typically still rely on traditional digital low-pass filters, occasionally combined with transmission windowing. The simplicity and straightforward implementation of these techniques have been difficult to challenge but limit their applicability for real use cases.

New conceptual approaches for transmitter waveforms have recently been described [i.8], [i.9], [i.10] and [i.11]. In particular, several ways to apply linear pre-coding prior to the OFDM FFT-modulation have been proposed. These techniques appear as a promising step towards next-generation spectrum-aware transmission schemes.

4.5.2 Protecting TV receivers by pre-coded OFDM

Regardless of the particular kind and purpose of CRS transmission scheme, CRS transmitters will be in full control over their out-of-band emission characteristics, if any claim on being a "cognitive" transmitter would be realistic. After all, not only should a certain frequency band be declared available, careful examination of the adjacent frequency bands should also take place before a CRS transmitter can start using the white space spectrum.

For CRS transmitters that exhibit high degree of frequency-isolation (low out-of-band emission) more white space will be available. It is therefore in the immediate interest of the CRS to assure low out-of-band power emissions. Traditionally, multi-carrier systems control their out-of-band emissions as illustrated in the top of figure 48. A low-pass filter is applied right after the base-band OFDM modulator.

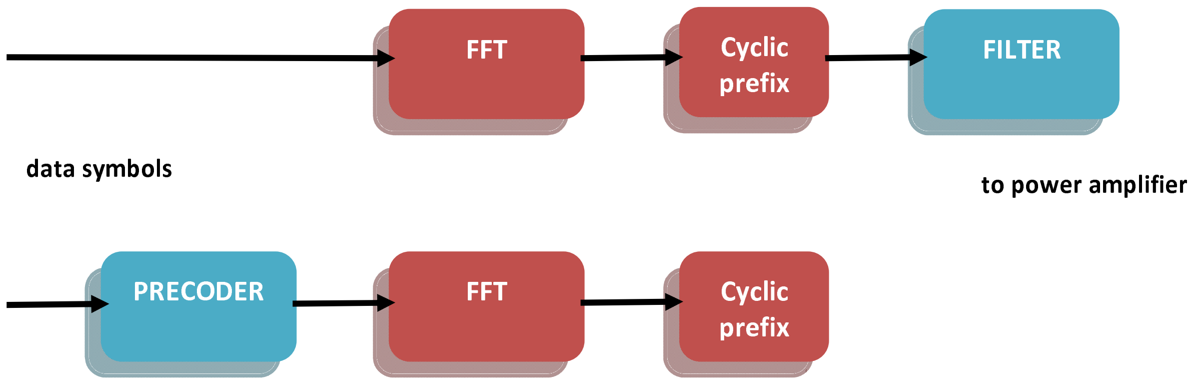
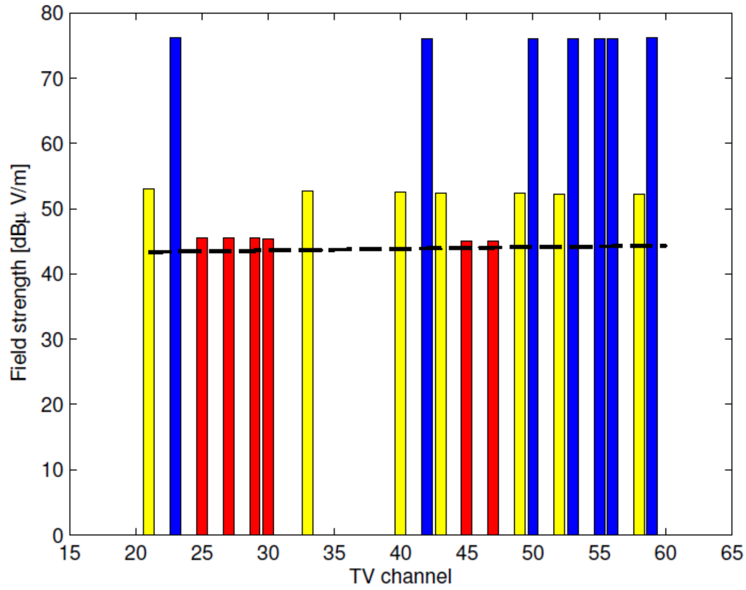


Figure 48: OFDM CRS transmitter means to protect TV receivers from harmful adjacent channel interference. Traditional, post-FFT, low-pass filtering (top) and advanced pre-coding (bottom)



NOTE 1: The different colours represent different TV transmitter field strengths, at a location just north of Stockholm.

NOTE 2: Loction (18.04W, 59:46N) is based on transmitter data provided by www.teracom.se/sandarinformation/hitta_ratt_tv_mast.

Figure 49: An example of the appearance of DTT transmissions in the UHF TV band channels 21 to 60

Meanwhile, the TV spectrum white spaces appear in an extremely scattered fashion. As an example, figure 49 illustrates the appearance of DTT transmissions in the UHF TV band channels 21 to 60 in a location just north of Stockholm, Sweden. Although white space is in the order of 50 % of the TV channels, proper exploitation of this white space will inevitably deal with the scattered nature of this white space. Deployment of larger bandwidths by CRS users will be done by multi-band transmission schemes (such as carrier aggregation schemes or multi-band OFDM).

For these scenarios, it appears that the traditional out-of-band power reduction techniques (filtering) are not suitable. Filters would be designed as notching filters and changing these filters in an agile manner may be difficult. These scenarios have prompted the design and implementations as illustrated in the bottom of figure 48. Here, the post-FFT filter has been replaced by a pre-FFT linear operation, known as pre-coding.

The main advantages of the pre-coding over the traditional means (filtering and/or windowing) are:

1) **Flexibility:** Traditional out-of-band power reduction techniques (filtering) are not suitable. Filters would be designed as notching filters and changing these filters in an agile manner may be difficult. It appears that the swift and transient-free adaptation of a pre-coder can be implemented much more convenient than a similarly adaptive post-FFT notching-filter.

2) **Spectral suppression performance:** For secondary transmitters that exhibit high degree of frequency-isolation (low out-of-band emission) more white space will be available. It is therefore in the immediate interest of the secondary to assure low out-of-band power emissions. The extent to which the pre-coder reduces the out-of-band emission is likely to be better than that of their traditional filtering/windowing counterparts.

3) **Performance in dispersive channels:** Performance in dispersive channels improves. While a low-pass filter inevitably increases the channel delay spread as it is perceived by the receiver (the receiver cannot distinguish between dispersion caused by the radio channel and that caused by the transmitter), a pre-coder does not. Hence, a system with a pre-coder can handle larger channel delay spreads.

The main challenges of the pre-coding over the traditional means (filtering and/or windowing) are:

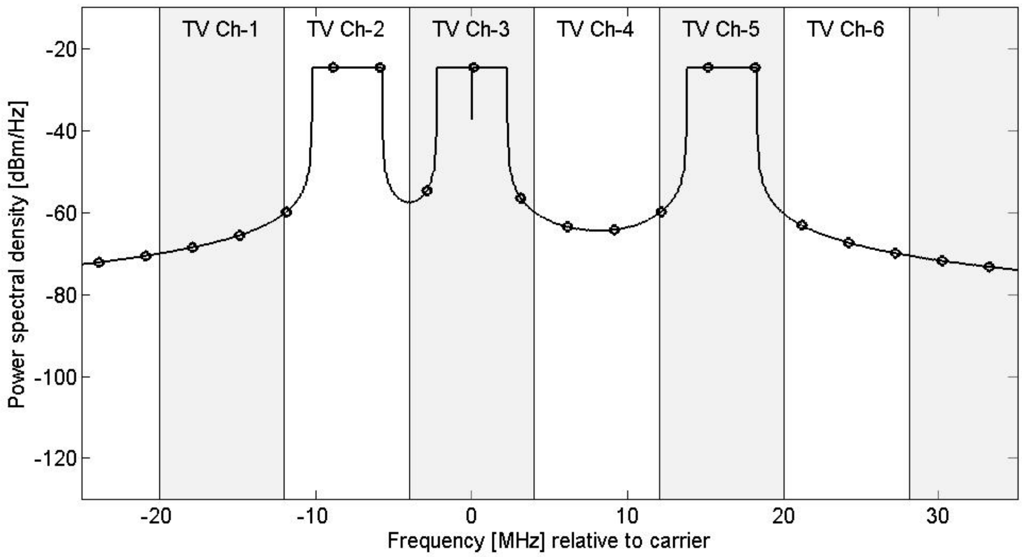
1) How can the excellent theoretical spectral suppression performance of the pre-coder be maintained under non-linear front-end distortions. This aspect has gained little attention in the literature.

2) In many contemporary standards the particular way to satisfy spectral requirements is not specified - means of power reduction are left to the vendor to design, and are only subject to a maximum EVM budget. If standardizing the pre-coding technique, EVM is freed for other transmitter operations. If not, how can good pre-coders be designed within the limits of this budget.

4.5.3 Pre-coder design

The purpose of this clause is to describe and evaluate the design of linear precoders that are suitable to suppress out-of-band emissions in what is sometimes referred to as *multi-band* OFDM. The key characteristic of multi-band OFDM is that the constituting sub-carriers are not necessarily contiguous in frequency. The LTE downlink with carrier aggregation is an example of this format.

Figure 50 illustrates the concept of multi-band OFDM for the deployment of LTE in 5 adjacent TV channels. Each TV channel can potentially be used by a 5 MHz LTE carrier. The entire multiplex is generated in one 40 MHz transmitter employing one large modulator FFT for the joint generation of the 5 carriers. By suitable choosing the sub-carriers (essentially switching on/off sub-bands of sub-carriers) incumbent protection can be guaranteed.



NOTE: The use of 5 TV channels (8 MHz each) by a multi-band OFDM system (having characteristics of three 5 MHz LTE carriers deploying 300 subcarriers each in the TV bands 2, 3 and 5). The TV channels 1, 4 and 6 are protected for potential incumbent use.

Figure 50: The (unshaped) spectrum of a multi-band OFDM signal (from simulations)

The problem addressed here is the suppression of the power in TV bands that are to be protected. The solutions employed in most of today's transmitters (low-pass filters suppressing the power outside a single LTE carrier) are not suitable here because also in-band TV channels need appropriate power suppression. In the example in figure 50 (which is from simulations) the fourth TV channel would not gain any protection from a classical 40 MHz wide low-pass filter.

Projection precoders

One class of spectral precoders in the literature, *projection* precoders, relevant for the reconfigurable radio systems is addressed here and are described and explored in the following. The projection precoders are linear operations represented by:

$$\bar{\mathbf{d}} = \mathbf{G}_p \mathbf{d} \tag{21}$$

where $\mathbf{d}$ is the column vector of K data symbols, $\bar{\mathbf{d}}$ is the column vector of K precoded data symbols, and $\mathbf{G}_p$ is the $K \times K$ pre-coder matrix. Instead of feeding the transmitter FFT with the modulation symbols $\mathbf{d}$, it is fed the precoded symbols $\bar{\mathbf{d}}$. The key characteristic of projection pre-coders in this class is that the precoder the matrix $\mathbf{G}_p$ is a *projection matrix* that orthogonally projects the vector $\mathbf{d}$ onto a linear subspace defined by a $M \times K$ matrix $\mathbf{A}$ in which all vectors have the same spectrum with suppressed out-of-band emission. The matrix $\mathbf{A}$ represents a set of M linear requirements on the transmitted symbols vector $\bar{\mathbf{d}}$ that uniquely specifies the spectrum characteristics. The linear subspace onto which $\mathbf{G}_p$ projects the data $\mathbf{d}$ is $\{\mathbf{x} : \mathbf{A}\mathbf{x} = \mathbf{0}\}$, all symbol vectors that satisfy the M equations $\mathbf{A}\mathbf{x} = \mathbf{0}$. By projecting the data vector $\mathbf{d}$ onto this subspace, the projection pre-coder guarantees that the resulting vector $\bar{\mathbf{d}}$ fulfils these equations and hence has the desired spectral characteristics represented by the matrix $\mathbf{A}$.

The choice of the matrix $\mathbf{A}$ uniquely determines the linear subspace (21), and also uniquely determines the orthogonal projection precoder $\mathbf{G}_p$ onto this subspace through (see [i.7]):

$$\mathbf{G}_p = \mathbf{I} - \mathbf{V}\mathbf{V}^H \tag{22}$$

where $\mathbf{V}$ is a size- $K \times M$ matrix obtained from the SVD (Singular Value Decomposition) of $\mathbf{A}$ and I is the identity matrix of size $K \times K$.

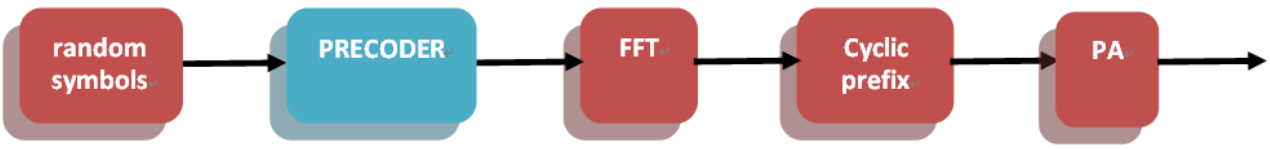
Literature specifies two choices of the matrix $\mathbf{A}$ that produce low out-of-band emissions. The first is based on a matrix $\mathbf{A}$ that requires the forces the OFDM trajectory to smoothly start and end in the origin. This causes the OFDM signal to become a *continuous phase modulation* (without the instantaneous phase transitions between consecutive OFDM symbols characterizing the un-precoded OFDM signals). The second choice is based on a matrix $\mathbf{A}$ that requires the OFDM spectrum to exhibit deep spectral notches at a set of well-chosen frequencies. In the performance example below this choice of the matrix $\mathbf{A}$ and the associated subspace and projector precoder is investigated.

NOTE 1: The actual choice of the precoder is determined by a few parameters. In the literature several criteria have been explored for the proper choice of $\mathbf{G}_p$. Besides the actual set of subcarriers operated by the OFDM transmitter, a precoder is uniquely characterized by a small set of *notching frequencies*. In the below performance evaluation example, this choice of notching frequencies is related to the TV channels operated and hence the indices of the used TV channels fully determine the pre-coder.

NOTE 2: The seemingly high complexity of the $K \times K$ transmitter matrix operation in (15) is only virtual. A truly low-complexity implementation is possible since the projection matrix is $\mathbf{G}_p = \mathbf{I} - \mathbf{V}\mathbf{V}^H$ where $\mathbf{V}$ is a size- $K \times M$ matrix, with $M << K$. The pre-coding (21) can hence be implemented with only $2M$ multiplications per sub-carrier (see [i.7]). The actual value of M is typically very small (the below example uses $M = 16$).

NOTE 3: The pre-coder operation (21) causes inter-subcarrier interference. A secondary receiver can eliminate the effect by a suitable receiver cancellation operation.

The following example shows the spectral suppression performance in the system shown in figure 50. Figure 51 shows a diagram of the simulated system. The spectral shaping potential of a system without other non-linear distortions (non-linear power amplifier, fixed-point representations, phase instability in local oscillators and mixers, etc.) is evaluated.



NOTE: The spectrum of the generated signal is estimated with Welch's periodogram algorithm.

Figure 51: The simulated transmitter operations

For a linear PA, the output signal's power spectrum can be computed analytically (provided the data symbols are uncorrelated). When the signal is ergodic, this power spectrum is the same as a long-term average of the squared moduli of short-term Fourier transforms (Welch's periodogram appoach to estimate power spectra). The power spectra shown in figure 52 were generated by such long-term averaging simulations and verified with analytical power spectrum expressions. For a non-linear PA only simulations results are carried out.

Again, figure 52 llustrates the example scenario of secondary deployment of five adjacent TV channels in Europe (8 MHz). Three 5 MHz LTE carriers (300 subcarriers each) are generated with one pre-coding transmitter $\mathbf{G}_p$. This precoder is designed according to the design criteria described above and the details in [i.10] and based on 16 notching frequencies (two closely spaced notches near -20 MHz, -16 MHz, -12 MHz, -4 MHz, 4 MHz, 8 MHz, 12 MHz and 20 MHz). These notches determine the matrix $\mathbf{A}$ which in turn determines the desired projection precoder though (23). Table 13 shows the details of this system and figure 52 shows the spectra of a plain OFDM signal (no precoding) and that of a precoded OFDM signal. The Figure shows the spectra for both a linear power amplifier and those assuming a non-linear amplifier obeying Rapp's non-linearity:

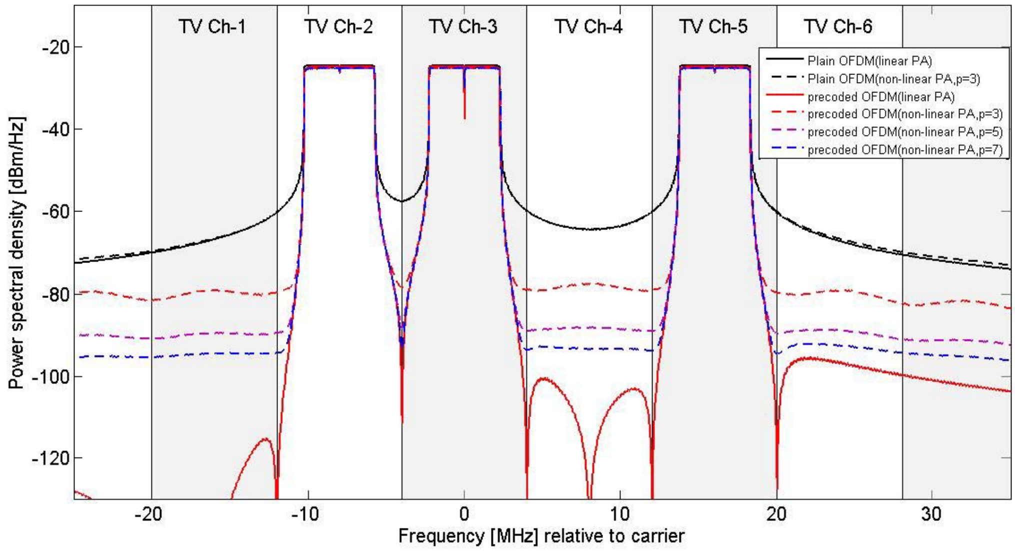
$$s(t) = \frac{s(t)}{\left(1 + \left(\frac{s(t)}{A_0}\right)^{2p}\right)^{1/2p}} \qquad (23)$$

for $p = 3$, 5 or 7, and $A_0 = 4$.

Table 13: Characterizing parameters for the secondary OFDM system and the precoder in figure 50

OFDM symbol length	1/15 ms
Cyclic prefix length	3/640 ms
Subcarrier spacing	15 kHz
Subcarrier indexes TV channel 1	-1 217,…, -1 068, -1 066,…, -917
Subcarrier indexes TV channel 2	-683, …, -534, -532, …, -383
Subcarrier indexes TV channel 3	-150, …, -1, 1, …, 150
Subcarrier indexes TV channel 4	383, …, 532, 534, …, 683
Subcarrier indexes TV channel 5	917, …, 1 066, 1 068, …, 1 217
Notch 1	-20 MHz ± 0,001 MHz
Notch 2	-16 MHz ± 0,001 MHz
Notch3	-12 MHz ± 0,001 MHz
Notch 4	-4 MHz ± 0,001 MHz
Notch 5	4 MHz ± 0,001 MHz
Notch 6	8 MHz ± 0,001 MHz
Notch 7	12 MHz ± 0,001 MHz
Notch 8	20 MHz ± 0,001 MHz

The power suppression in the TV bands 1, 4 and 6 used by incumbents is in the order of 80 dB, and 70 dB for the linear and the non-linear PA models if better non-linear PA is used. Notably, no traditional post-FFT filtering or pulse shaping is employed.



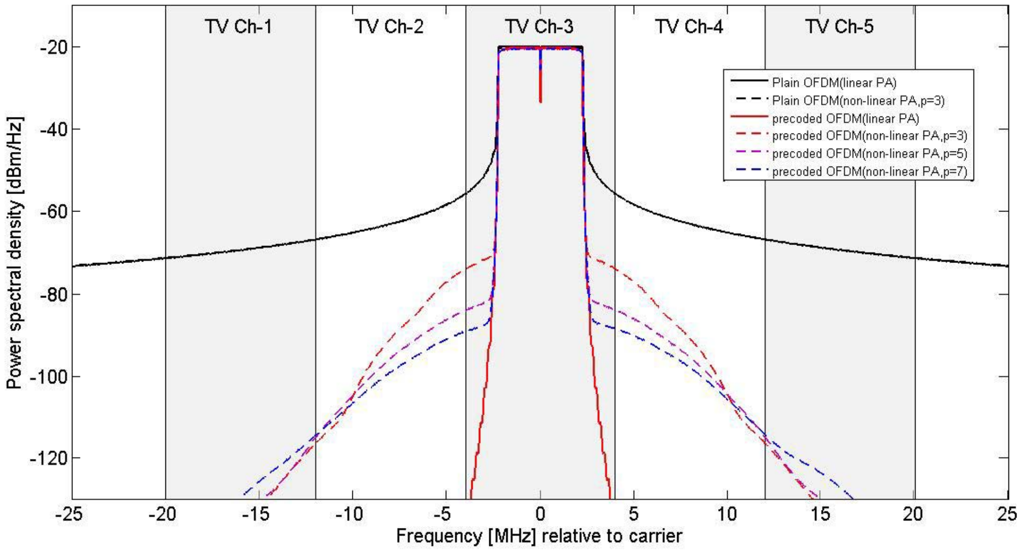
NOTE: Solid lines indicate the spectrum assuming a linear amplifier, dashed lines indicate the spectrum for a non-linear amplifier with different p values in eq. (23). Different *p* values denote different non-linear amplifier performance. Three 5MHz LTE carriers (300 subcarriers each) are generated with a precoding transmitter. Channels 1, 4 and 6 are protected (Results are from simulations).

Figure 52: Example scenario of secondary deployment of 6 adjacent TV channels in Europe (8 MHz)

Finally, table 14 and figure 53 show the details of a second configuration where only one channel is available and the other 4 channels are protected. For the non-linear PA, again, suppression is more than 70 dB in any of the protected channels if better non-linear PA is used.

Table 14: Characterizing parameters for the secondary OFDM system and the precoder in figure 53

OFDM symbol length	1/15 ms
Cyclic prefix length	3/640 ms
Subcarrier spacing	15 kHz
Subcarrier indexes TV channel 3	-150, …, -1, 1, …, 150
Notch 1	-8 MHz ± 0,001 MHz
Notch 2	-4 MHz ± 0,001 MHz
Notch3	4 MHz ± 0,001 MHz
Notch 4	8 MHz ± 0,001 MHz



NOTE: Solid lines indicate the spectrum assuming a linear amplifier, dashed lines indicate the spectrum for a non-linear amplifier with different p values in eq. (23). One 5 MHz LTE carriers (300 subcarriers) is generated with a precoding transmitter. Channels 1, 2, 4 and 5 are protected (results are from simulations).

Figure 53: Example scenario of secondary deployment of 5 adjacent TV channels in Europe (8 MHz)

4.5.4 Signalling related to pre-coding

The purpose of this clause is to describe the consequences and needs of the above-described pre-coder solutions on the air-interface-signalling of the secondary system, along with indicating potential ways to perform this signalling.

There are typically two regimes for the pre-coder to operate. In the first regime, the pre-coder is *transparently* implemented in the secondary transmitter in the sense that a secondary receiver is not aware that the transmitter uses a pre-coder. In the context of existing cellular standard specifications, the distortion introduced by the vendor-specific transmitter pre-coder should be accounted for in the specified EVM-budget. In this regime air-interface signalling is not needed since pre-coding is transparent.

In a second regime, the transmitter pre-coder is explicitly accounted for in the specifications of a secondary systems and left outside of the EVM budget. In this regime, the secondary receiver will be informed by the secondary transmitter through suitable signalling protocols about the actual choice of the transmitter pre-coder. This will allow a secondary receiver to actively use this information to reduce the impact of the distortion (which is not possible under the first regime where the EVM will cause a performance reduction).

In the remainder of this clause the signalling issues and requirements associated with the second regime are further discussed.

The pre-coder examples in clause 4.5.3 are independent of the transmitted data - the pre-coder coefficients are constant as long as the spectral occupancy of the secondary signal is not changed. Thus, the signalling accounting for updating the pre-code coefficients at the receiver only needs to occur when the spectral containment of the secondary signal is changed (due to for instance an appearing incumbent signals). The secondary transmitter typically changes its spectrum occupancy from time-to-time according to interference level measurements by the network, or any other policy decisions. It is likely that in these occasions, a number of other signalling messages will be passed between the secondary transmitter/receiver pair. Pre-coder information could be embedded in these messages.

At the time instants when the spectral content of the signal changes (and hence the pre-coder changes), the pre-coding information to convey to the receiver is the new pre-coding matrix G defined in the previous clause. This size-KxK matrix consists of K^2 entries, with little apparent correlation. Typically K is very large (for instance, K=300 in 5 MHz LTE) and the transmitting all the entries (with sufficient precision) would impose a huge overhead to the system. Straightforward compression schemes are available.

First the decomposition by the singular-valur decomposition as defined in the previous clause would allow to convey the factor matrix V instead of the entire pre-coder G. Matrix V has size *KxM* where *M* is very small (*M* is typically 10-20). This would still necessitate the signalling of 3 000-6 000 numbers with high precision which is a prohibitively large number of bits.

While this would reduce the overhead significantly there are even more obvious ways to compress the signalling overhead into a small message such that signalling overhead is reduced and the downlink is not overly burdened by this signalling.

Typically, the secondary transmitters determine when and how to update the pre-coder. Once this decision is made it needs to be passed to the relevant secondary receivers. While a pre-coder essentially is characterized by the pre-coder matrix G in clause 4.5.3, there are many ways to compress this information into just a few bits.

A first assumption is based on the fact that a system can operate well with a finite (relatively small) number of spectral pre-coders, where each pre-coder represent one mode of operation, one way to occupy the spectrum. The UHF TV band consisting of fixed-bandwidth TV-channels is well suited for this approach. The system could just define a number of standard combination of TV channels that is occupied by the secondary system. Each of these combinations then is associated with a unique OFDM pre-coder.

In this regime, the secondary base station informs the relevant secondary mobile units about the pre-coder to use by signalling an *index in a codebook*, rather than the entire pre-coder matrix. Each codebook-index then represents one way to occupy the spectrum (which TV channel, or which combination of TV channels). The codebook and the associated pre-coders are known by both the secondary transmitter and receiver, and each pre-coder in the codebook is designed to minimize the out-of-band interference for its relevant associated spectral content.

If there are L different pre-coders in a codebook these are represented with $\log_2 L$ bits. Suppose there may be up to L=128 (considering that a secondary OFDM system covers up to say 7 contiguous TV channels (56 MHz) then each of these TV channels can be used or not, and hence there are 2^7=128 possible spectral configurations) different pre-coders to choose from (representing the different spectral containments of the system), in which case there will be 7 bits needed in the message. Considering these 7 bits only need to be signalled when the pre-coder changes, this is a very small overhead.

The use of a predefined codebook ensures that the signalling has small signalling overhead and does not burden the spectral efficiency of the radio link.

The design of the codebook is not obvious (i.e. which pre-coders should be included). The particular pre-coder examples in clause 4.5.3 is for instance characterized in that they force the spectrum of the OFDM signal to be zero at pre-defined notching frequencies $f_0 \dots f_M$. A codebook could then for instance contain pre-coders for various different choices of sets of notching frequencies. $f_0 \dots f_M$.

4.6 WSD operating parameters based on WSD emission characteristics

This clause proposes and evaluates mechanisms for handling different WSD emission characteristics when determining the operating parameters for WSD operating in UHF TV band white spaces.

4.6.1 Approaches for determining the allowed WSD operating parameters based on WSD emission characteristics

This clause discusses approaches for determining the available channels and location specific maximum allowed output power based on the emission characteristics of the WSD. These approaches may be considered for using the calculation model presented in ECC report 159 [i.3] (clause 4.3). The current CEPT model enables location-specific maximum output power for available channels. The WSD receives information from the geo-location database about the available channels and also the allowed output power levels for those channels. The CEPT model enables more flexible and efficient spectrum use than the current FCC model [i.1] in which the maximum output power depends on the WSD type. According to the CEPT model, the WSD may be allowed to operate with low power on areas/channels which would not be allowed for operation if fixed output power was used. Also, the WSD may be allowed to use higher power in some geo-location areas or channels.

In the current CEPT model, when determining the maximum allowed output power for a WSD, the emission characteristic of the WSD should be taken into account to prevent adjacent channel emissions from interfering with the incumbent users (e.g. the adjacent channel leakage ratio (ACLR)). The WSDs may have different emission characteristics depending on the radio standard in use and the implementation. Some WSD, for example, may support mechanisms such as spectral pre-coding to constrain their emission characteristics to limit harmful interference to the adjacent channels (spectral pre-coding is further discussed in clause 4.5).

This clause discusses two different approaches: the database (DB-) centric and the WSD- centric. The difference in the approaches is whether the geo-location database or the WSD calculates the allowed operating parameters for the WSD. In both approaches the geo-location database has the knowledge of the maximum allowed emission levels at each geo-location. The allowed emission level for a channel defines the maximum EIRP that the WSD may emit on that channel at a given geo-location. The level ensures tolerable performance for all incumbent users in the area. The tolerable incumbent user performance is used to derive the tolerable interference power level on each channel (as in-block and/or out-of-block power), at the target reference location points to be protected. From the tolerable interference power levels at these geo-locations, path loss models are used to calculate the allowed emission levels at the WSD geo-location. For an incumbent user at the same geo-location as the WSD, ECC report 159 [i.3] defines reference geometries and the resulting minimum coupling losses between the WSD and the incumbent, which are used instead of the path loss models. Note that the aggregated interference from multiple WSDs at an incumbent user should be taken into account either as fixed margin or as proposed in clause 4.2.2. In determining the WSD operating parameters, the emission characteristics of the WSD and the allowed emission levels at the geo-location are used to determine the maximum power level for the WSD. In the DB-centric approach the WSD provides information of its emission characteristics to the geo-location database, which determines the available channels and the maximum allowed output power on each channel for the WSD. In the WSD-centric approach the geo-location database provides the maximum allowed emission levels on each channel to the WSD, and the WSD determines its operating parameters, i.e. channel and output power, based on its emission characteristics (e.g. ACLR).

4.6.1.1 DB-centric model

In this approach, the geo-location database calculates and provides to the WSD the maximum allowed EIRP for each allowed channel at the WSD's location. The ECC report 159 [i.3] outlines this general approach, but does not consider different WSD emission characteristics in the calculations. The report indicates the maximum output power would be calculated for each geo-location and for each device type/class. The report notes that it is important that technical standardization bodies specify the ACLR of WSDs for use by geo-location databases. However, the device parameters such as the ACLR may depend on the implementation and possible advanced mechanisms that the WSD may support to improve its performance. Also, the WSD standards may evolve and enable improved devices parameters. In addition, for example, parameters such as the ACLR may depend on the WSD temperature and the operating output power.

The DB-centric model uses a limited set of pre-defined parameters for the WSD emission characteristics. These parameters may be derived from the WSD standards. The pre-defined parameters enable efficient communication of the WSD emission characteristics to the geo-location database and their management in the geo-location database. The geo-location database performs the calculation only for the pre-defined emission characteristics. The following example illustrates how the allowed WSD operating parameters can be determined with DB-centric approach:

1) DB has pre-knowledge of:
   - Incumbent locations and their emission characteristics, or their operation/coverage areas. Incumbent use timing:
     - From this information the DB can pre-calculate the allowed emission levels at each geo-location for each channel.
   - Predefined set of allowed WSD emission characteristics, i.e. bandwidth and emission masks/ACLR:
     - The emission characteristics may be bundled into sets for device types or classes. For example, as different standards and implementations may have differing bandwidth and emission mask/ACLR combinations, they may be grouped separately. However to limit the range of calculations, the calculation may be based on a limited set of WSD emission characteristics. These may be parameters which are defined by the standards defining radio standards for UHF WSD.
2) WSD provides its ID, geo-location, and emission characteristics (based on the predefined parameters), when requesting available spectrum information from DB.
3) DB calculates and provides the allowed channels and allowed EIRP for those channels to the requesting WSD.

4) WSD selects its operating channel and operates with/below the allowed EIRP on that channel.

5) WSD provides the information of the selected operating parameters to the geo-location database or a separate advanced geo-location engine (see, for example, clause 4.2.2).

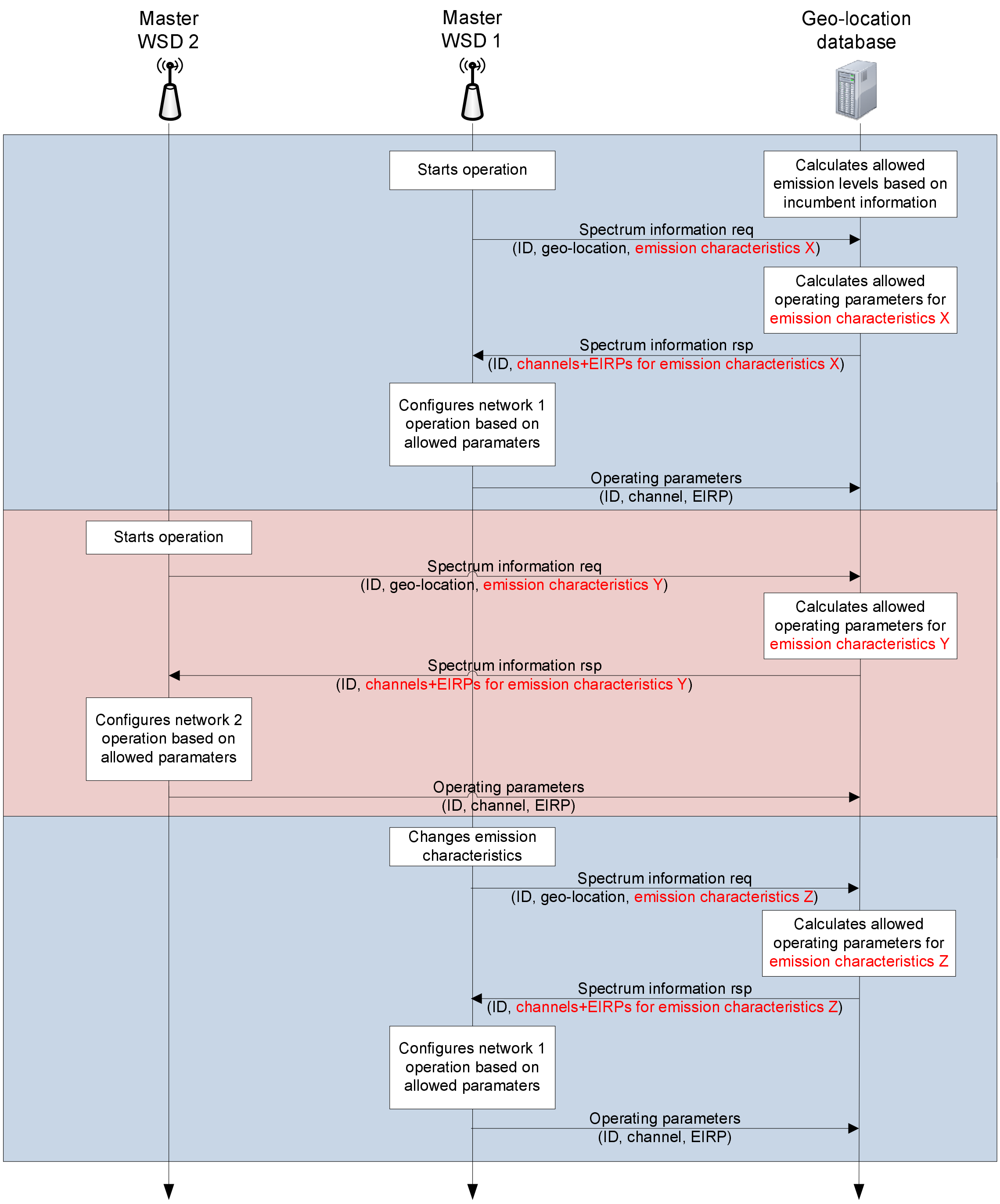


Figure 54: Example information flow for determining operating parameters in DB-centric model

Figure 54 presents an example information flow for the DB-centric model. Firstly, WSD1 requests the allowed operating parameters for its location from the geo-location database. In the request WSD1 provides its geo-location and its emission characteristics. The geo-location database calculates the available channels and allowed EIRP in each channel, and provides them to WSD1. WSD1 selects its operating channel and EIRP from the received information, and configures its network to operate accordingly. WSD1 informs the geo-location database of the selected operating parameters if required by the regulation or the protocol to access the database.

Secondly, WSD2 requests the allowed operating parameters for its location and for its emission characteristics. Because WSD2 emission characteristics are different than WSD1 emission characteristics, the geo-location database calculates and provides available channels and allowed EIRPs in each channel based on the emission characteristics of WSD2. WSD2 selects its operating parameters, configures its network, and informs the geo-location database of the selected operating parameters if required by the regulation or the protocol to access the database.

Thirdly, the emission characteristics of WSD1 change. They may change, for example, if the WSD starts performing spectral pre-coding or if elements of its network WSDs change. WSD1 requests the new allowed operating parameters from the geo-location database.

It is assumed that WSDs (in the example WSD1 and WSD2) know the emission characteristics of any slave WSDs in their networks, and are responsible for configuring the network according the allowed parameters. The slave WSDs are not presented in the figure 54.

4.6.1.2 WSD-centric model

In this approach the geo-location database provides to the WSD the allowed emission levels for each channel. The WSD is responsible of selecting its operating parameters, i.e. channel and EIRP, and that its emissions do not exceed the allowed emission levels in any of the channels. This is illustrated in figure 55. In this approach, the calculation of the allowed operating parameters based on WSD emission characteristics is performed by the WSD.

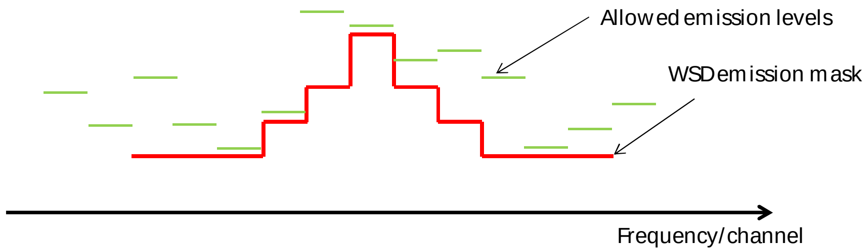


Figure 55: WSD emission mask matched to meet the allowed emission levels

An example of how the allowed WSD operation parameters can be determined with WSD-centric approach:

1) DB has pre-knowledge of incumbents-related information (their locations, their emission characteristics, their operation/coverage areas, use timing, etc.). From this information the DB can pre-calculate the allowed emission levels at each geo-location for each channel.

2) WSD provides its ID and geo-location, when requesting available spectrum from the DB.

3) DB provides the allowed emission levels (e.g. dBm/Hz) for each channel to the WSD.

4) WSD selects the operating parameters by finding the best match for its own emission mask with the allowed emissions (according to the ACLR or capabilities such as spectral pre-coding).

5) WSD provides the information of the selected operating parameters to the geo-location database or a separate advanced geo-location engine (clause 4.2.2).

Figure 56 presents an example information flow for the WSD-centric model.

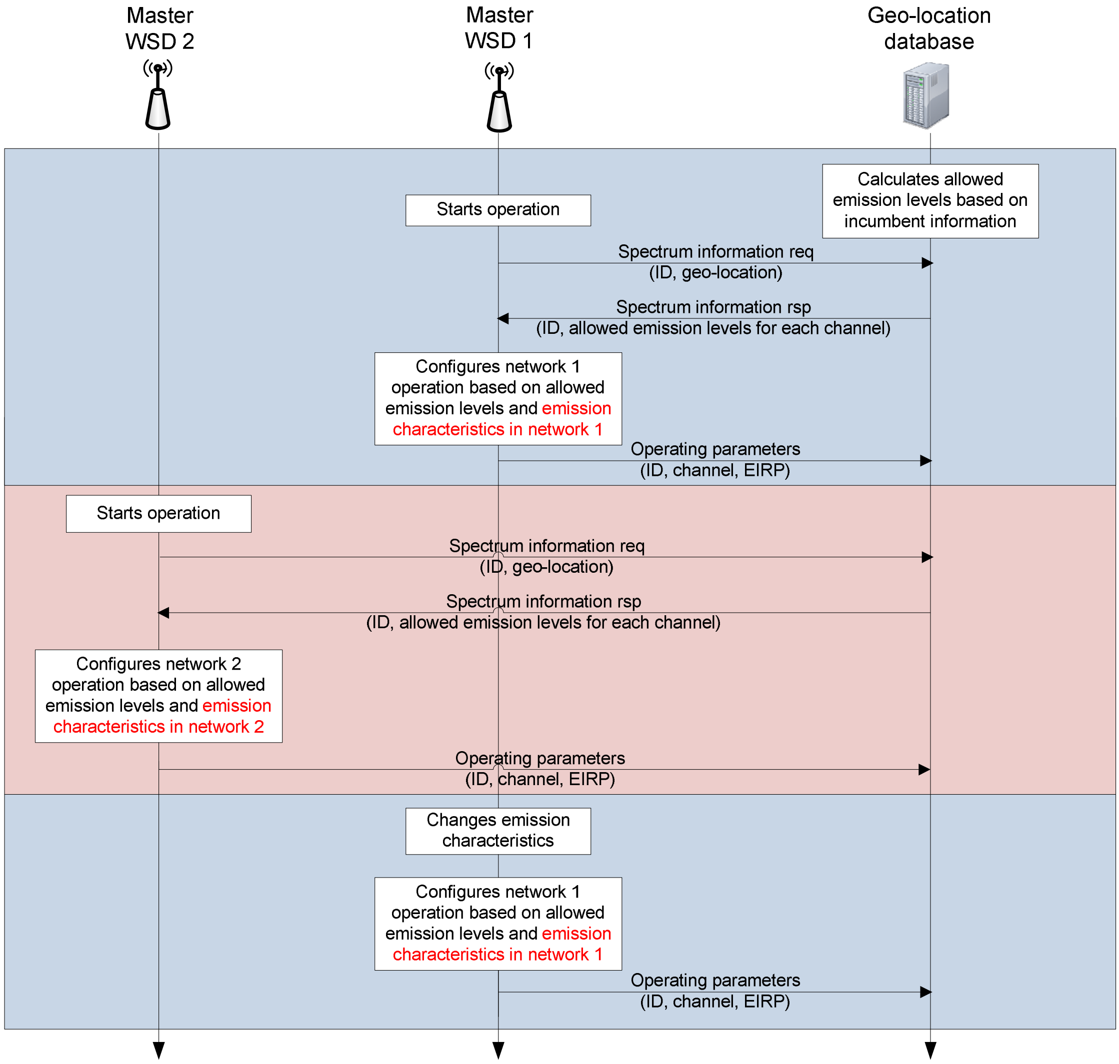


Figure 56: Example information flow for determining operating parameters in WSD-centric model.

Firstly, WSD1 requests the allowed emission levels for its location from the geo-location database. In the request the WSD1 provides its geo-location. The geo-location database provides the allowed emission levels for each channel to the WSD1. WSD1 selects the operating channel and its operating parameters according to the allowed emission levels received from the database and accounting for its own emission characteristics (e.g. according to the ACLR and possibly according to feature capabilities such as spectral pre-coding). The WSD1 configures its network to operate according to those operating parameters. WSD1 also informs the geo-location database of the selected operating parameters if required by the regulation or the protocol to access the database.

Secondly, WSD2 requests the allowed emission levels for its location. The geo-location database provides the allowed emission levels for each channel to WSD2. These parameters may, for example, be the same as provided to the WSD1 if the WSDs have the same geo-location. The WSD2 selects the operating channel and EIRP according to the allowed emission levels received from the database, and its own emission characteristics, and configures its network accordingly. The WSD2 also informs the geo-location database of the selected operating parameters if required by the regulation or the protocol to access the database.

Thirdly, the emission characteristics of WSD1 change. They may change, for example, if the WSD changes its spectral pre-coding or if the elements of its network WSDs change. The WSD1 does not have to request information from the geo-location database if it has not changed its geo-location, or the validity of the previously requested information has not expired. The WSD1 re-selects the operating channel and operating parameters according to the allowed emission levels already received from the database, and its own changed emission characteristics.

It is assumed that the WSD (in the example WSD1 and WSD2) knows the emission characteristics of the slave WSDs in its network, and is responsible for configuring the network according the allowed parameters. The slave WSDs are not presented in the figure.

4.6.1.3 Discussion of the DB-centric and WSD-centric models

In the DB-centric approach, a limited set of pre-defined parameters for the WSD emission characteristic is accommodated. This pre-defined parameter set enables efficient communication and management of the WSD emission characteristics in the geo-location database. The WSD should conform to the pre-defined set of parameter values, and there is a limited set of compliance tests to define. However, the limited set of pre-defined WSD emission characteristics also affects the spectrum efficiency because the pre-defined parameters create some granularity. If new standards or implementation mechanisms, which enable better emission characteristics, evolve, there may be a need to add new pre-defined parameter sets. Adding new parameters later may be slow, because the support would need to be implemented across many geo-location databases. Another challenge with this approach may be that, in practice, the emission mask may depend on the device temperature and the output power. In this approach the WSD output power is not fixed, but is provided by the geo-location database after the WSD query. If WSD gives only its "worst case" emission characteristics, its emission characteristics may be better than the worst case on the given channel and selected output power, and thus the spectrum use may not be the most efficient.

In the WSD-centric approach there is no limited set of pre-defined WSD emission characteristics, and thus no granularity to decrease the efficiency and flexibility. Because the WSD selects its operating parameters itself by matching its actual operating mask to the allowed emission levels, the geo-location database only needs to calculate and store the allowed emission levels. In this approach, the emission levels are defined for each geo-location pixel. They are the same for all WSDs at the same geo-location. There is only one allowed emission level value for each pixel and each frequency. This simplifies the DB design and reduces the amount of signalling and the interaction with the WSDs.

The WSD-centric approach however requires more calculations in the WSD as the WSD determines its operating parameters. It should be assured that each WSD is able to select the operating parameters in a way that the allowed emission levels are not exceeded. In the WSD-centric approach, the WSD should obtain information about the allowed emission levels on both the channels allowed for operation (the "white space" channels) and channels which actually are not allowed for operation (the incumbent occupied channels), to enable the WSD to avoid causing adjacent channel interference on the occupied channels. This extra information increases the amount of channel information that the geo-location database provides to the WSD compared to the DB-centric approach. On the other hand the information that the WSD provides to the geo-location database decreases, particularly if the WSD has means to modify its emission characteristics.

5 Co-existence studies out of CEPT responsibility

5.1 Coexistence between Incumbent and Cognitive Radio Systems in UHF TV band White Spaces

A significant amount of study has been done on incumbent service protection by some organizations. Sensing and geo-location database technology are exploited as the candidate technologies to determine the available spectrum for WSDs from the point of view of preventing the interference caused by WSDs to incumbent service.

However coexistence study between TV system and CRS not only involves estimation of TV system performance but also involves estimation of CRS performance. As mentioned in clause 10.1.4 of [i.3], the previous study didn't take into account the fact that WSDs and incumbent service may interfere with each other.

An example of this co-channel coexistence problem is shown in figure 57; TV system is operating in frequency channel F1 in a certain region. From the viewpoint of previous study, such as FCC, F1 is available for CRS only when the distance between the contour of TV system and the WSD's coverage edge is larger than separation distance d1 representing the minimum geographical distance to protect incumbent service out of the interference caused by CRS.

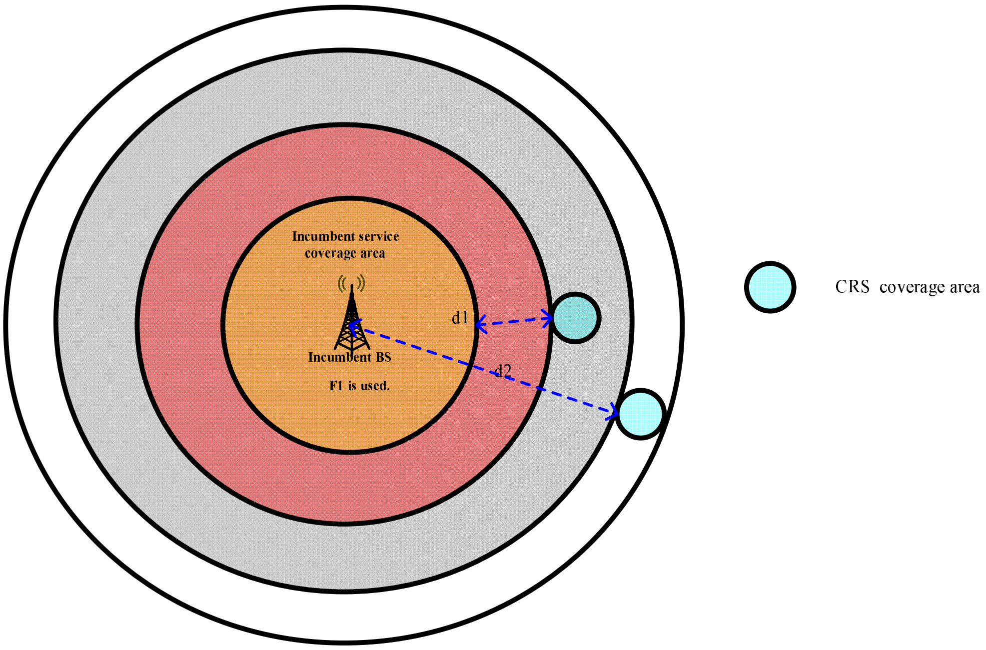


Figure 57: An example of the problem

In this scenario, WSDs may be informed that F1 can be utilized in the area filled with gray color based on sensing or geo-location database. However, WSDs cannot achieve desired performance due to the interference from incumbent service operating in F1 until the distance between the contour of CRS and the BS of incumbent service is larger than separation distance d2 which is the minimum geographical distance to protect the target CRS. The example mentioned above shows the problem in determining available frequency for CRS from the perspective of co-channel coexistence, while the similar issue may exist in judging whether adjacent channel to incumbent service is available for CRS.

Thus the performance of TV system and CRS should be studied in this clause taking in consideration bidirectional co-channel/adjacent channel interference. On the precondition that TV system has been protected, the realistic capacity of CRS should be re-examined in view of interference stemming from TV system. This is also listed as part of further study in clause 11 of [i.3]. Meanwhile, solutions which enable efficient use of spectrum by CRS based on the estimation is provided in the following clause.

5.1.1 RF performance of LTE systems under adjacent channel interference from DTT systems

5.1.1.1 Coexistence scenario

Based on information from the geo-location database, an LTE system may be allowed to operate in the UHF band TVWS on a channel adjacent to a DTT transmitter. Depending on the regulatory framework, the LTE system may be required to transmit with a certain maximum power in order to protect the DTT transmitter. For instance, in the FCC framework, personal/portable devices may operate in the first adjacent channel to a TV station as long as their transmit power is below 40 mW, in order to reduce the risk of harmful interference [i.1]. In Europe, the allowable transmit power for a system operating in a channel adjacent to that which is used by a neighbouring TV station may depend on several factors described in the present document such as the WSD location, ACLR characteristics, and bandwidth. In both regulatory frameworks, a WSD may be allowed to transmit in an adjacent channel to a DTT where it is close enough that the leakage of DTT signal into the adjacent channel causes interference to the WSD.

Figure 58 illustrates a typical coexistence scenario for an LTE system operating in UHF TV band WS in a channel adjacent to one reserved for DTT transmission. Interference from DTT into the adjacent band is more pronounced in locations close to the DTT transmission tower. In addition, in such locations, the WSD transmit power will likely be reduced compared to scenarios where the WSD is located far from the DTT coverage area. As a result, the most likely coexistence scenario to consider for an LTE system operating in a channel adjacent to DTT transmission is that of the small cell scenario (pico or femto cell) as shown.

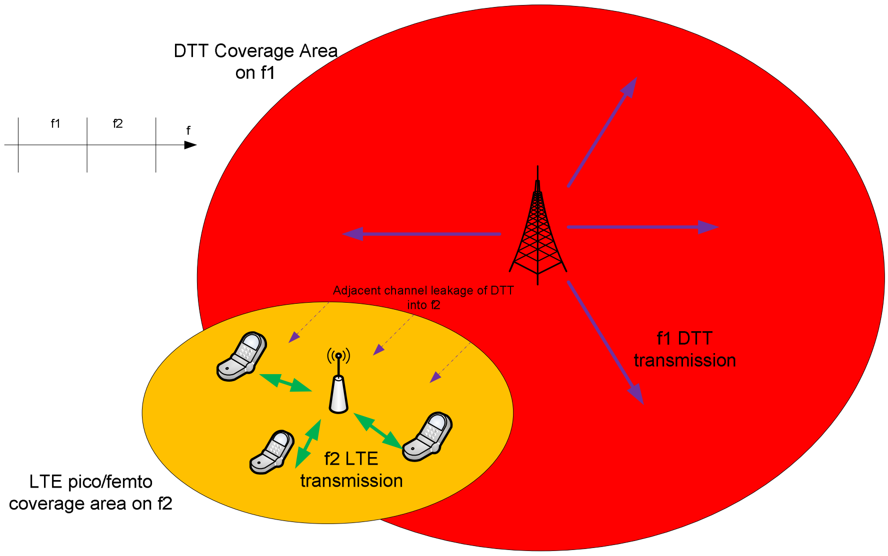


Figure 58: Coexistence Scenario for DTT Adjacent Channel Interference into LTE Small Cells

The DTT interference signal level seen by a UE or eNB operating close to a DTT broadcast station can be estimated using the DTT spectral transmission mask and an applicable channel propagation model. Such a channel model should also account for changes in the interference on the channel as well as mobility. The accepted transmission mask for DVB-T in Europe is shown in figure 59, where the lower curve (sensitive cases) has been used in coexistences studies made by CEPT [i.14].

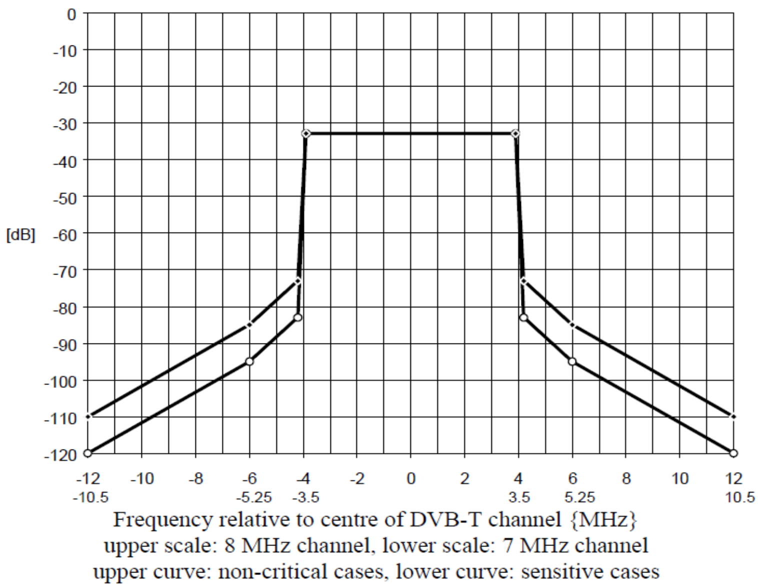


Figure 59: DVB-T Spectrum Mask for DVB-T in bands shared with other services [i.15]

An applicable propagation model can then be used to determine the worst-case power density of the interference at a given distance of the LTE UE or eNB from the DTT broadcast station. One of the most widely used propagation models for radio frequency propagation is the Hata Model for Urban, Suburban, and Rural areas. The Hata model covers point-to-point and broadcast communications with frequency ranges of 150 MHz to 1 500 MHz, link distances between 1 km and 20 km and transmitter antenna height between 30 m and 200 m. Other propagation models may also be used in the analysis, depending on the frequency, distance, antenna height, and specific feature of the propagation that needs to be modelled for that specific analysis.

Figure 60 shows the path loss experienced by the interference based on the Hata model with the following parameters:

Table 15: Hata Model Constants considered for DTT Transmission Station

Frequency	fc	600 MHz
Transmission Antenna Height	hte	150 m
Receiver Antenna Height	hre	1,5 m

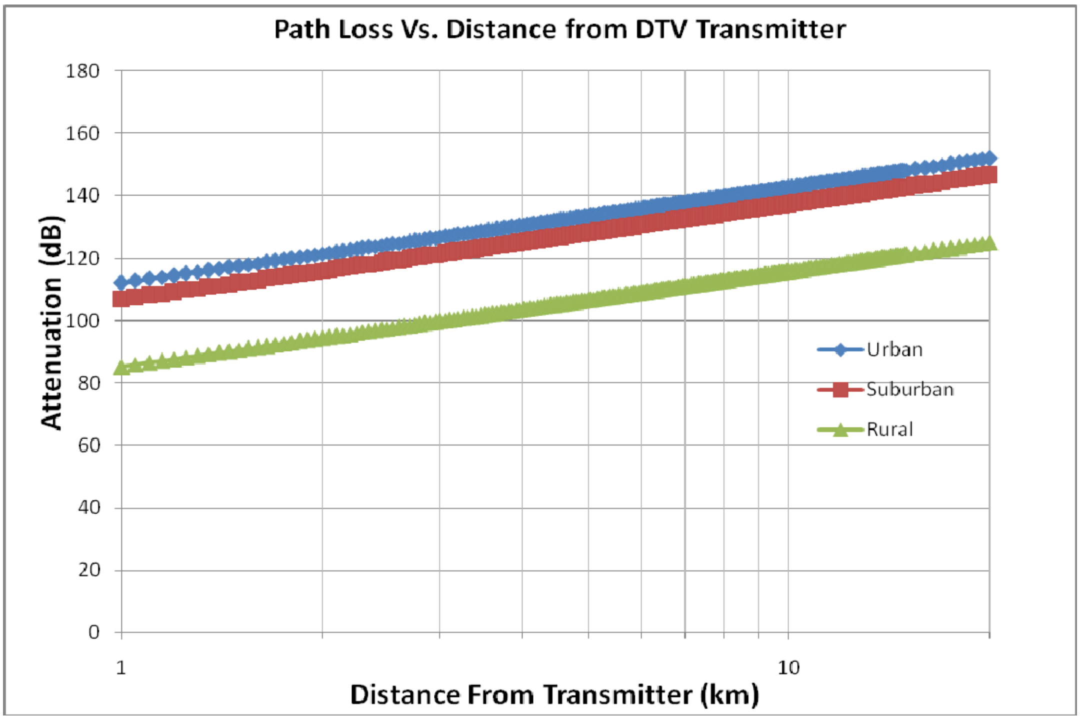


Figure 60: Path Loss versus Distance from DTT Transmitter using table 15 Constants

For example, if a UE or eNB is located at 1 km from a high-powered DVB-T transmitter in a rural area with total output power at 400 kW (86 dBm), and an immediate attenuation at the edge of the band of 50 dB, the interference seen by the UE or eNB will be at 86 - 50 - 80 = -44 dBm. Such interference would be considered quite high for an LTE system and may significantly impact its performance.

The impact of interference on the LTE system itself is further qualified by the Adjacent Channel Selectivity (ACS) of the LTE system. The ACS of the LTE system is the measure of the receiver's ability to receive a signal at its assigned channel frequency in the presence of an adjacent channel signal at a given frequency offset from the centre frequency of the assigned channel. ACS is the ratio of the receive filter attenuation on the assigned channel frequency to the receive filter attenuation on the adjacent channel(s).

ACS requirements are defined by 3GPP for both a UE (in [i.16]) and an eNB (in [i.17]). For example,table 16 illustrates the ACS requirements for the UE provided the adjacent channel interferer is up to -25 dBm [i.16]. On the other hand, requirements for the eNB are stated in terms of throughput reduction only. In other words, specific scenarios for an interfering system in the adjacent bands are specified and the eNB is expected to maintain > 95 % of the maximum throughput for the reference measurement channel. In this case, analysis requires comparison between the interfering signal used in the scenarios specified in [i.17] and a DTT interferer.

Table 16: UE ACS Requirements [i.16]

		Channel bandwidth
Rx Parameter	**Units**	**5 MHz**
ACS	dB	33,0

In the above example, assuming a 33 dB ACS at the receiver, the interference power seen by the LTE system due to receiver imperfections would be given as 86 dBm - 80 dB - 33 dB. The overall system performance (taking into account contributions of both ACS and ACLR) can then be obtained by computing the effective ACIR of the system (1/ACIR = 1/ACS + 1/ACLR) to determine the effective interference power level experienced by the LTE UE/eNB.

Based on simulation results and/or analysis of existing LTE deployments, an allowable interference power level to ensure the required LTE performance can be determined and mapped to corresponding distance using the Hata model curves in the figure above or an alternate channel model if a distance other than the range of distances applicable for the Hata model (1 km-20 km) is being considered.

In addition, it can be observed from the DVB-T spectral mask behaviour that there is a variation of 40 dB in the DVB-T interference power level measured at opposite ends of the adjacent channel. The interference observed by a UE or eNB operating over the adjacent channel (assuming the entire adjacent channel is used) will be 40 dB greater at the edge of the channel closest (in frequency) to the DTT-reserved channel compared to the edge farthest (in frequency) from it. This additional information should be included in the performance analysis/simulation, and can also be used by the LTE system to its advantage in order to operate more efficiently in the adjacent channel.

For LTE, characterizing the performance impact of the adjacent channel interference requires consideration of data and control information separately. Data is transmitted in resource blocks which are generally localized over a set of subcarriers spanning a subset of the used frequency band. On the other hand, control information uses Control Channel Elements (CCEs) which consist of Resource Element Groups which are interleaved over the entire frequency band. The figure below illustrates a simplistic example of the effect of interleaving on the resulting location of the resource element groups which make up a CCE. A single CCE is composed of 9 resource element groups. Each resource element group consists of four consecutive usable (non-reference symbols) symbols within a resource block. The 9 resource element groups which comprise the CCE, however, are spread over the entire control channel bandwidth by the interleaver function.

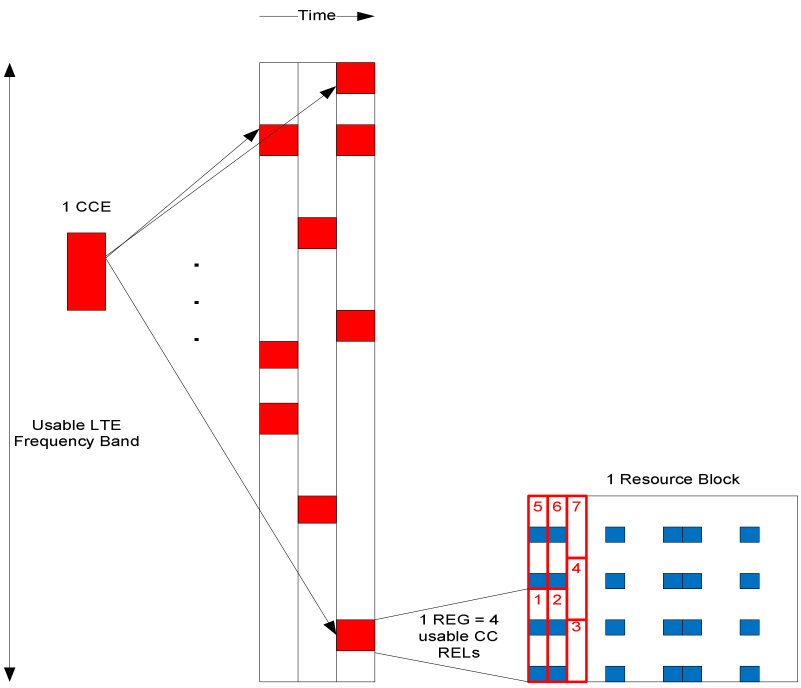


Figure 61: Mapping one CCE to 9 REGs on the LTE Control Channel

While the data in an LTE system can adapt to a static frequency selective fading characterized by this scenario by avoiding bad resource blocks, control information is spread evenly over the entire band and will be adversely affected. This performance needs to be evaluated under the consideration of the interference level variations on the TVWS channel (caused by the DTT mask on the adjacent channel) and the actual bandwidth selected for use by the LTE system. In addition, analysis/simulation should consider to specific sub-cases of this scenario, namely, the effect of DTT on the eNB and on the UE.

5.1.1.2 Analysis/simulation results

To evaluate the impact of the adjacent channel interference from a DTT transmitter on the LTE physical downlink control channel (PDCCH) performance, link level simulations were run to measure the PDCCH BLER. This clause presents PDCCH simulation results for an LTE system operating in the presence of adjacent channel interference from a DTT channel with a transmission mask as shown in figure 59 of clause 5.1.1.1.

The link level test bench models Rel-8/10 compliant PDCCH transmission and reception, the propagation channel, and a DTT transmitter operating in the adjacent channel. The high level block diagram of the test bench is shown in figure 62.

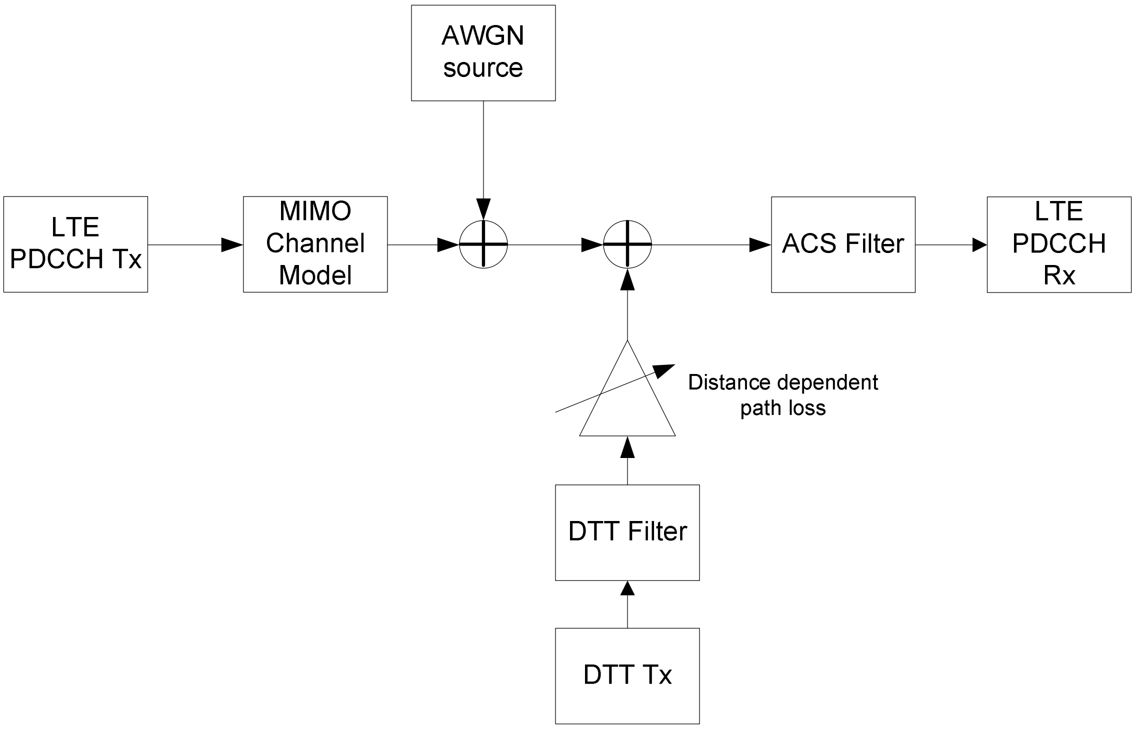


Figure 62: High level block diagram of the link level simulation bench

In the simulation bench illustrated above, the LTE PDCCH Tx, the channel model and the AWGN block are calibrated to set the desired SNR at the input of the UE receiver (LTE PDCCH Rx block). The variable attenuator is used to model the distance dependent path loss, which, for the purpose of this simulation, was set to the Hata model with the parameters of table 15. The DTT filter generates a DTT signal which respects the DTT transmission mask, while the ACS filter simulates the adjacent channel selectivity (ACS) achieved by an LTE UE.

In the test bench, the LTE system is configured to use the adjacent channel in such a way that it maximizes the frequency separation between the LTE and the DTT channel. The BW of the LTE transmission is parameterized and can be selected as 3 MHz or 5 MHz. This is shown in figure 63.

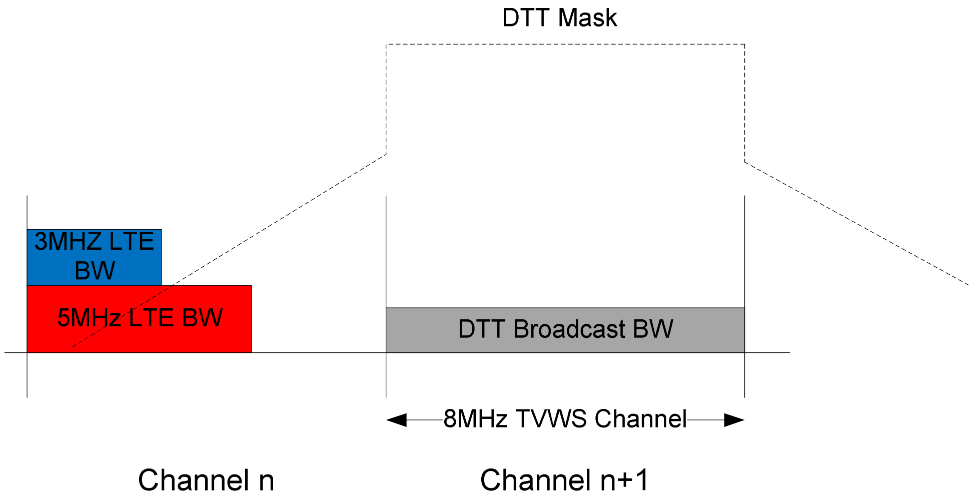


Figure 63: Configuration of the LTE Channels within the Adjacent Channel

The above selection of the configuration of the LTE channels has been made in order to compare the two systems (a 3 MHz LTE system and a 5 MHz LTE system) under the condition that they are operating in the best scenario (i.e. so that they both try to minimize the interference from the adjacent channel DTT signal by maximizing the frequency separation). In this way, the two systems also share a common control channel space of 3 MHz (at the leftmost edge of channel n), and the effect of an additional 2 MHz of control channel BW utilized by the 5 MHz LTE system in frequencies that approach channel n+1. This configuration was preferred to other potential configurations of the channel (e.g. the two LTE systems operating using the same centre frequency) because it provides a more fair comparison of the systems when each operates at their optimal configuration and will show the maximum performance difference between the two systems.

Some relevant simulation configuration parameters are shown in table 17. The parameters from table 17 correspond to the PDCCH conformance test defined in [i.16]. The channel model specified by the conformance test in [i.16] is EPA5; this is a frequency selective channel over the 5 MHz bandwidth. To enable a fair comparison of the 3 MHz and 5 MHz configurations of the control channel, our simulation use a frequency flat AWGN channel instead of the EPA5. The use of EPA5 (a channel model defined over 5 MHz) resulted in an unfair advantage of the 3 MHz over the 5 MHz channel, and the purpose of the simulation results was to compare only the effects of the adjacent channel interference.

Table 17: Link level test bench parameter configuration

Parameter	Value
Channel model (for the LTE link)	AWGN
Path loss model (for the adjacent link)	Hata
Distance between the DTT transmitter and the UE (km)	Parameterized, variable in the range of 2 km to 10 km
LTE channel BW (MHz)	5 MHz and 3 MHz
Number of tx antennas	4
Number of rx antennas	2
PDCCH DCI format	DCI 2
PDCCH payload (excluding the CRC)	42 bits
PDCCH aggregation level	2 CCE

Figure 64 shows the simulated PDCCH BLER versus the SNR for various distances between the DTT transmitter and the UE when the LTE control channel is configured for 5 MHz BW. For validation purposes and to determine the baseline for the chosen set of parameters, a simulation was run with the DTT disabled (the curve labelled "5 MHz, DTV disable" in figure 64). For large distances between the DTT and the UE (e.g. 10 km), it can be seen that the PDCCH BLER performance is almost the same as the baseline performance in the absence of the DTT interferer. As expected, the PDCCH performance degrades as the LTE UE is closer the DTT tower. For example, a degradation of about 3,4 dB SNR is experienced at 4 km distance, for the target PDCCH BLER of 1 %. The degradation is even larger for a distance of 3 km (about 5 dB degradation at 1 % BLER, compared to the no DTT interference case).

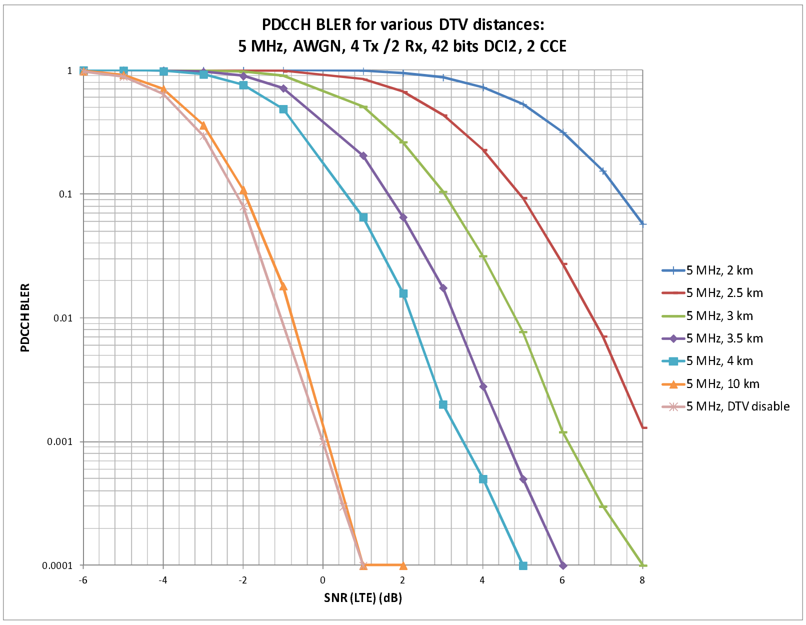


Figure 64: PDCCH BLER vs. SNR (not including Interference) (control channel BW = 5 MHZ) and various distances to DTT

A similar set of simulations was run with the LTE control channel configured for 3 MHz BW. The simulation results for the 3 MHz PDCCH BW are shown in figure 65. As in the case of 5 MHz BW, for test bench validation purposes, a simulation was run with the DTT disabled. The results for large distance (10 km) between the DTT and the LTE are virtually the same as the "DTT disabled" case.

When the 3 MHz case is compared to the 5 MHz case for a given (fixed) distance, the performance of the 3 MHz PDCCH BW is better than the performance of the 5 MHz PDCCH BW configuration. Note that when the PDCCH is configured for the 3 MHz BW, certain control channel elements located closer in frequency to the DTT transmitter that would have been used in the 5 MHz PDCCH are not used in the 3 MHz case.

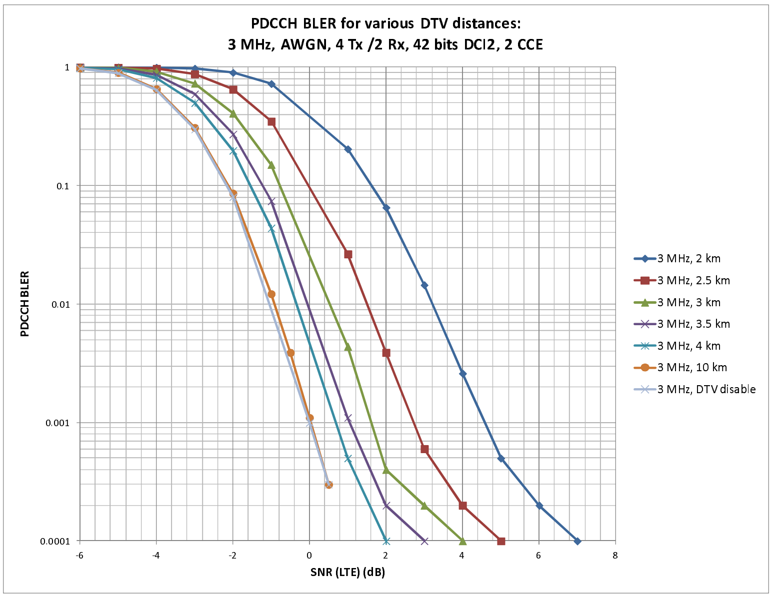


Figure 65: PDCCH BLER vs. SNR (not including Interference) (control channel BW = 3 MHZ) and various distances to DTT

For comparison purposes a subset of the curves presented in figures 64 and 65 for the 3 and 5 MHz BW are combined on the same plot and shown in figure 66. More specifically, the BLER performance for a distance of 2 km, 3 km and 4 km is shown for both 3 MHz (blue solid line) and 5 MHz (red dashed line) PDCCH BW. It is interesting to note that for all distances considered, the 3 MHz control channel configuration mitigates better the adjacent channel interference, as compared to the 5 MHz control channel configuration.

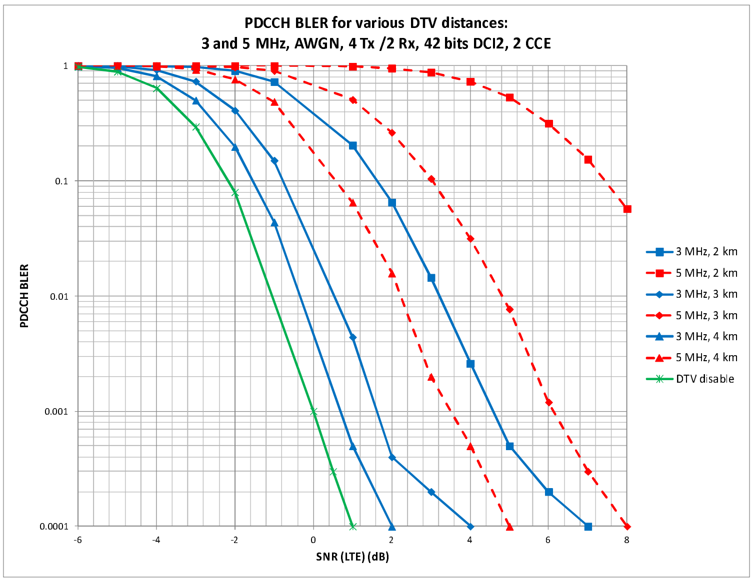


Figure 66: Comparison of PDCCH BLER between control channel BW = 5 MHZ and 3 MHz

The simulation results presented above show that the LTE control channel performance can degrade significantly due to interference from a neighbouring DTT broadcaster in an adjacent channel. Since the use of a 3 MHz channel avoids mapping PDCCH bits in resource elements which reside closer (in frequency) to the channel reserved for DTT transmission, the 3 MHz control channel BW can perform several dB better in the neighbourhood of a DTT station.

A possible way to mitigate the interference from an adjacent channel DTT transmitter is to increase the coding gain of the PDCCH, by reducing the coding rate. For a given payload of the DL control channel (the number of bits carried by the selected DCI format), the coding rate can be reduced by increasing the CCE (Control Channel Element) aggregation level. The CCE aggregation levels supported in LTE Rel-8/10 are 1, 2, 4 and 8 CCEs.

Link level simulations were run for the 5 MHz PDCCH BW, using the same parameters as defined in table 17, and increasing the CCE aggregation level from 2 to 4. To enable a fair comparison of the results, the same DCI format 2 and the same number of bits were used as for the simulations of figures 62 to 65.

The simulation results for CCE aggregation 2 and 4, and for various distances between the adjacent channel DTT transmitter and the LTE receiver, are shown in figure 67. It should be noted that the SNR on the x-axis represents the UE receive SNR without taking into account the DTT interference as part of this noise (only channel noise is used in the SNR computation).

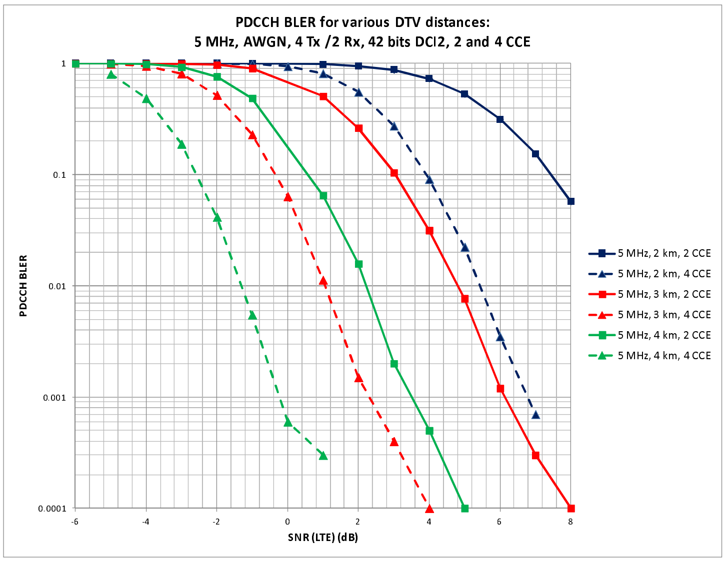


Figure 67: PDCCH BLER vs. SNR (not including DTT interference) for various CCE aggregation levels

The results of figure 67 show that increasing the PDCCH CCE aggregation level from 2 to 4 results in significant improvement of the PDCCH BLER performance, which is due to the increased coding gain.

As a next step, it is interesting to compare the performance of PDCCH with increased CCE aggregation, to the performance of the reduced BW PDCCH. The baseline configuration is the 5 MHz BW using CCE aggregation level of 2, in the presence of the adjacent channel DTT interferer. When configuring the PDCCH BW to 3 MHz, the maximum PDCCH capacity (i.e. the maximum number of PDCCH that can be signalled in the available BW), reduces by a factor of 5/3 as compared to the baseline (BW=5 MHz, CCE=2).

To enable a fair comparison between the two methods (increased CCE aggregation vs. reduced BW), only an aggregation level of 4 CCE is simulated. This way, the maximum PDCCH capacity reduces by a factor of 4/2=2 with respect to the same baseline (BW=5 MHz, CCE=2), so the reduction in the PDCCH capacity with the increased CCE aggregation is comparable to the reduction of 5/3 in the reduced BW case.

The side-by-side simulation results are shown in figure 68.

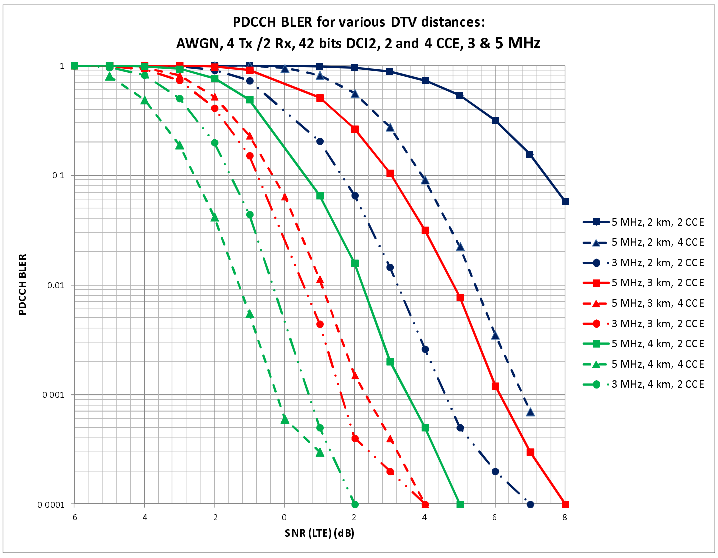


Figure 68: Performance comparison for different CCE aggregation and PDCCH BW

From figure 68, it is interesting to note that when the LTE receiver is closer to the adjacent channel DTT transmitter (e.g. 2 km or 3 km), the lower PDCCH BW outperforms the increased CCE aggregation approach. This is likely due to the fact that closer to the adjacent channel DTT transmitter, the adjacent channel DTT interference is the main cause for performance degradation, so positioning the PDCCH resources further away in frequency domain from the interferer is very effective as it avoids the physical resources most impacted by the adjacent channel interferer.

As the LTE receiver is located further away from the DTT transmitter (e.g. 4 km), the increased CCE aggregation option outperforms the reduced BW. This is likely due to the fact that further away from the adjacent channel interferer, the impact due to the adjacent channel DTT interference is reduced, so increasing the coding gain by increasing the CCE aggregation is a more effective solution.

5.1.1.3 Coexistence suggestions

Based on the simulation results presented in clause 5.1.1.2, performed under the assumption of an AWGN channel, it appears that both the reduction of the effective BW of the control channel and the increase in the CCE aggregation level are feasible approaches to mitigate the impact of the adjacent channel interference from a high power DTT transmitter on the PDCCH performance. Moreover, reducing the control channel BW appears to be more effective for smaller distances between the DTT transmitter and the LTE receiver, while increasing the CCE aggregation level is more effective at larger distanced to the DTT transmitter.

5.1.2 RF performance of LTE systems in presence of co-channel signals from DTT systems

5.1.2.1 Coexistence scenario

Depending on the regulatory framework, a secondary system may be allowed to operate in the UHF TVWS outside the coverage area of a co-channel incumbent system. The geo-location database provides the technical parameters for operation by a secondary system i.e. separation distance and the maximum E.I.R.P to protect the incumbent system. These limitations help to guarantee that the secondary system does not cause harmful interference to the co-channel incumbent system. However, a WSD may experience co-channel interference from the incumbent system in such cases.

Therefore, it is very important to avoid the co-channel interference from the incumbent to the secondary cognitive radio systems (CRS). In this clause, the interference from a DTT system to a CRS with small cell operation has been investigated via simulations. Based on the simulation results, some suggestions on the deployment of the CRS are given to avoid such interference to the CRS.

5.1.2.2 Analysis/simulation results

Figure 69 illustrates a typical scenario for a LTE system operating in UHF TV band in a co-channel with a DTT system. The coverage radius of the DTT system is denoted by *R*2, and the coverage radius of the LTE system is denoted by *R*1; and the geographical separation of these two systems is D.

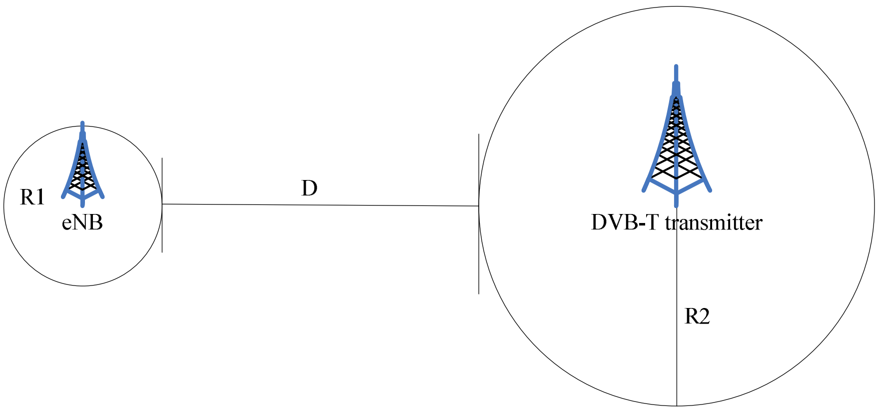


Figure 69: Simulation scenario

The DTT interference signal level seen by a UE can be estimated by an applicable channel propagation model. The resulting downlink received SNR of the co-channel UE can be calculated as $SNR = \frac{P_{eNB}}{N_0 + I_{DTT}}$ where P_{eNB} is the received signal power at the UE from the eNB, N_0 is the level of the Gaussian white noise, and I_{DTT} is the interference from the DTT system seen by the UE.

The received signal power P_{eNB} is calculated with the transmit power at the eNB set as the maximum E.I.R.P. as indicated by the geo-location database for the incumbent protection [ECC report 159 [i.3]]. The interference from the DTT system can be calculated as:

$$I_{DTT} = P_{DTT} - PL_{DTT} \tag{24}$$

where P_{DTT} is transmit power of the DTT broadcast station, and PL_{DTT} is the path loss.

The target of the simulation is to examine the average SNR of the WSDs in the LTE system and to compare this with the minimum performance requirements for a specific test for PDCCH in the TS 136 101 [i.16]. In the simulations, the coverage radius of the DTT system *R*2 is set as 31,15 km, and the coverage radius of the LTE eNB *R*1 is ranging from 100 m to 500 m. The separation distance D is fixed to be one of {1 km, 2 km, 5 km} to cover 3 different cases. Other simulation parameters and information of the channel models can be found in table 18.

Table 18: Simulation settings

Parameters	value
Operating frequency	700 MHz
Channel model between UE and eNB	ETU
Propagation model between UE and eNB	Okumura
Propagation model between eNB and DVB-T receiver at the edge of DVB-T coverage	Recommendation ITU-R 1546 [i.6]
Coverage radius of eNB within E-UTRA frequency bands	100 m - 500 m (*R1*as shown in the figure 69)
Coverage radius of DVB-T transmitter	31,15 km (*R2* as shown in the figure 69)
Number of antenna of UE	1
e.i.r.p. of DVB-T transmitter	72,15 dBm [from ECC Report 159 [i.3]]
Max e.i.r.p. power of eNB based on [ECC Report 159 [i.3]] for 1 km, 3 km, and 5 km, respectively	12,9 dBm, 18,9 dBm, and 22,6 dBm
UE Speed	3 km/h
Height of DVB-T transmitter	150 m
Height of eNB	20 m
Height of UE	1,5 m
SNR threshold	2,6 dB
Shadowing loss standard deviation	5,5 dB [from ECC Report 159 [i.3]]
Multiple interference margin for 4 interferes (MI)	6 dB [from ECC Report 159 [i.3]]
safety margin (SM)	20 dB [from ECC Report 159 [i.3]]
protection ratio	23,1 dB [from ECC Report 159 [i.3]]

NOTE 1: The simulation considers the worst case analysis because the shadowing is not considered.

NOTE 2: The UE is dropped 4 000 times within the coverage of *R1* randomly. Then we calculate the SNR for each 'drop', and get the average SNR.

NOTE 3: We select 150 m as the height of the DTT transmitter and 20m as that of the eNB, which is close to the assumption specified in 3GPP TR 36.814 [i.32]. The selected values can avoid interpolation for height to use (Recommendation ITU-R P.1546-4 [i.6]). The height of UE is set to 1,5 m as in 3GPP TR 36.814 [i.32], which belongs to the range specified in Recommendation ITU-R P.1546-4 [i.6].

Figure 70 shows some simulation results of the relationship between the coverage radius of the LTE system and the received SNR of the UE for different fixed separation distance D. According to the LTE standards [i.16], the SNR of at least 2,6 dB is needed for the transmission in PDSCH (QPSK, coding rate 1/3, SISO, 50RB). This threshold (2,6 dB) is highlighted in green in figure 70 to identify whether this lowest required SNR can be satisfied. It should be noted that since a SISO system is employed, the threshold which is used to show the limiting cell radius in the simulation results which follow will be more conservative, given that most systems would use two transmit antennas. In this case, a system with two transmit antennas would be able to operate over a much larger cell radius than what is shown in the results below. The 2,6 dB threshold is calculated as follows:

Table 8.2.1.1.1-2 in TS 136 101 [i.16] shows the reference SNR (-0,4 dB). The corresponding antenna configuration is 1x2 Low.

$$SNR_{SISO} = SNR_{SIMO} + Gain_{diversity} + Gain_{MRC} \tag{25}$$

Where:

- $Gain_{MRC}$=3 dB
- $Gain_{diversity}$ is depend on the channel. If we consider the worst situation, then $Gain_{diversity}$=0.
- SNR_{SIMO} = -0,4 dB.

And therefore: SNR_{SISO} = -0,4 + 0 + 3 = 2,6 dB.

For the separation distance *D*=1 km (the red line in figure 70), it can be observed that a LTE eNB with the maximum allowed transmit power for the co-channel DTT protection can only support a coverage radius of 230 m. For a LTE eNB whose coverage radius is larger than 230 m, it needs to measure the interference on the TVWS channel provided by the geo-location database. If this TVWS channel cannot guarantee the coverage of the LTE eNB, the eNB may consider reducing the coverage while operating on this TVWS channel.

For the separation distance *D*=2 km (the blue line in figure 70), the LTE eNB with the maximum allowed transmit power for the co-channel DTT protection can support a coverage radius of less than 300 m. For the separation distance D=5 km (the yellow line in the figure), the LTE eNB can support a larger coverage. For a shorter separation, both lower maximum EIRP and larger co-channel interference from the incumbent system limits the cell coverage.

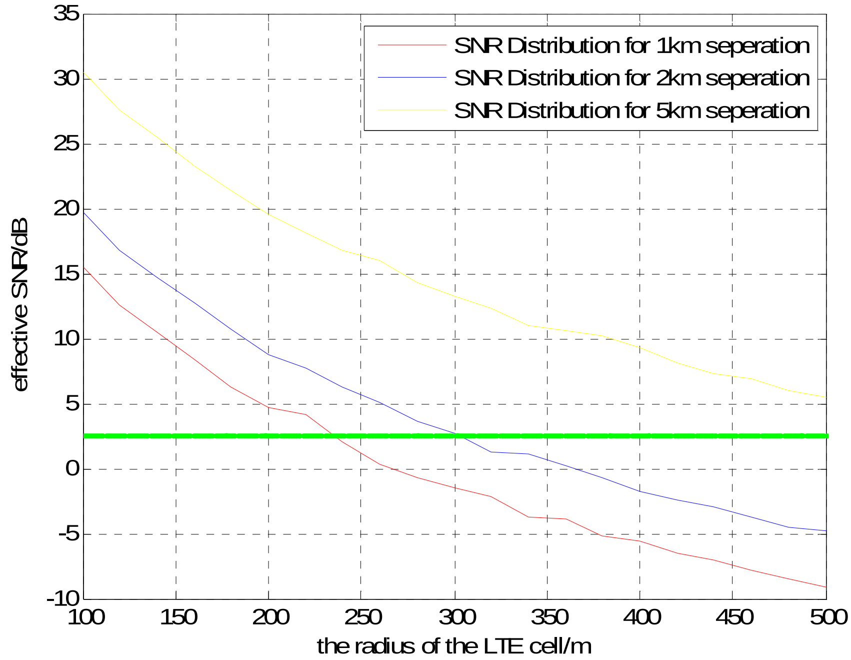


Figure 70: SNR vs eNB coverage radius

5.1.2.3 Coexistence suggestions

Based on the above simulation, it can be seen that in a certain geographical area with the DTT transmit parameters assumed in the simulations, and under the small cell operations simulation assumptions used to obtain the above results (DTT transmit power, quoted models for the path loss, etc.), the maximum transmit power allowed by the geo-location database may allow for the use of LTE cells with smaller cell radius. One reason is that short separation distance results in low maximum transmit power, in addition to the interference from DTT. For a given separation distance, a coverage radius threshold can be calculated to find the cell size in which the LTE cell under the small cell operations can coexist with the DTT system.

5.2 Coexistence between Cognitive Radio Systems in UHF TV band White Spaces

This clause describes the coexistence scenario between the secondary CRSs in the UHF TV band white spaces. It also describes and evaluates different mechanisms to enhance the coexistence among CRSs. In this clause it is assumed that the spectrum access in TV band white spaces is unlicensed. The CRS has ability to determine channels that are locally unused by incumbent users, e.g. by accessing a geo-location database, or by spectrum sensing, and it can freely operate on those channels within the regulatory limits. Coexistence problems occur if two or more CRSs cause emissions in the same geo-location area, in the same channels, and at the same time. The coexistence problems degrade the performance of the CRSs. There are various coexistence mechanisms which CRSs may use to improve the coexistence. In this clause the mechanisms are divided in non-coordinated and coordinated coexistence solutions.

5.2.1 CRSs coexistence scenario description

This clause describes the coexistence scenario and problem. The CRS networks which operate on unlicensed TV white spaces may be independent networks and networks operated by different operators. Also they may be implemented with different radio technologies. The networks may operate on the same geo-location area and do not explicitly know the existence of each other. This causes coexistence challenges. The network planning is typically performed among the networks of an operator. However, in the unlicensed spectrum there may be also other networks which may change their operation parameters according to their spectrum need and evaluation of the radio environment. Also, the availability of TV white spaces may change depending on the incumbent operation. Some technologies implement self-coexistence mechanisms which enhance the coexistence of networks using that technology. However, all the networks may not use the same technology in the unlicensed spectrum.

The coexistence is a local matter. It concerns the networks which service areas and interference areas (see the definitions below) overlap, and which are capable of causing emission on the same channel at the same time. Those networks may interfere with each other, and thus they need to be considered when managing the coexistence. The coexistence problem of the networks is solved if the networks do not interfere with each other. Figure 71 presents two exemplary coexistence scenarios for four networks. On the left side the networks 2 and 4 have a coexistence problem because their service areas overlap and they operate on the same channel, at the same time. On the right, the coexistence problem is solved by changing the network 4 operating channel. Other option to solve the problem would be timesharing the channel 1 between network 2 and 4.

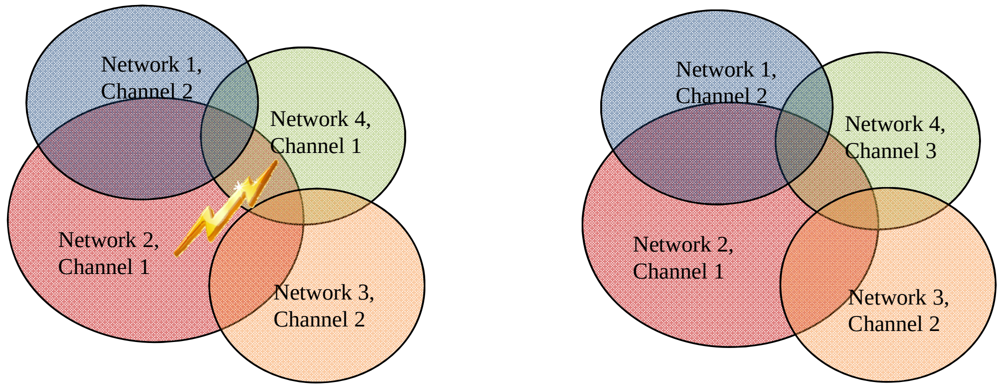


Figure 71: Networks with and without coexistence problem

Service area:

The service area is the area within which the network nodes successfully communicate.

Interference area:

The interference area is the area within which emissions from the network nodes exceed an interference threshold. It is typically larger than the service area.

Whether the network may cause interference to the other network or suffer from interference caused by the other network depends on whether the service areas or the interference areas of the networks overlap. The networks which do not overlap at all, or overlap only on their interference areas, do not cause interference to each other's communication. These networks do not have a coexistence problem, and thus they are not considered to belong to each other's coexistence set. This scenario is illustrated in figure 72a.

Mutual interference:

A scenario in which the networks may cause mutual interference to each other, for example the networks which interference areas overlap the service areas of each other may cause interference to each other's communication. This scenario is illustrated in figure 72b.

Non-mutual interference:

A scenario in which a network may cause interference to the other network, for example the network which interference area overlaps with the service area of the other network may cause interference to the other network's communication. The other network however does not cause interference to the network, if its interference area does not overlap with the service area of the network. This scenario is illustrated in figure 72c. In that figure the network 1 is the interference source and the network 2 is the interference target.

Coexistence set:

When determining the operating parameters for a network, the operation and limitations of the networks with overlapping service area and interference areas (mutual and non-mutual interference cases) should be considered. Those networks can be considered to belong to the coexistence set of the network. As an example in figure 71:

- Coexistence set of network 1: networks 2 and 4.
- Coexistence set of network 2: networks 1, 3, and 4.
- Coexistence set of network 3: networks 2 and 4.
- Coexistence set of network 4: networks 1, 2, and 3.

Note that a change in the network operation parameters may directly affect the networks in its coexistence set, but also indirectly to the networks which do not belong to its coexistence set. An example of such scenario:

1) Network 1 in figure 71 on the right discovers that it cannot operate on channel 2 anymore; only channels 1 and 3 are available. The network 1 decides to operate on channel 3 because it is less congested than channel 1.

2) Network 4, which belongs to the coexistence set of the network 1, operates on channel 3 and is impacted by this change. The network 4 evaluates the channels, and discovers that it can operate on channel 2, which is now less congested than channel 3.

3) Network 3, which is not in the coexistence set of the network 1, but is in the coexistence set of the network 4 is impacted by this change.

When managing the coexistence in coordinated manner, the limitations caused by the coexistence sets of the other networks should also be considered to avoid domino effects when changing the operating parameters changes of the coexisting networks.

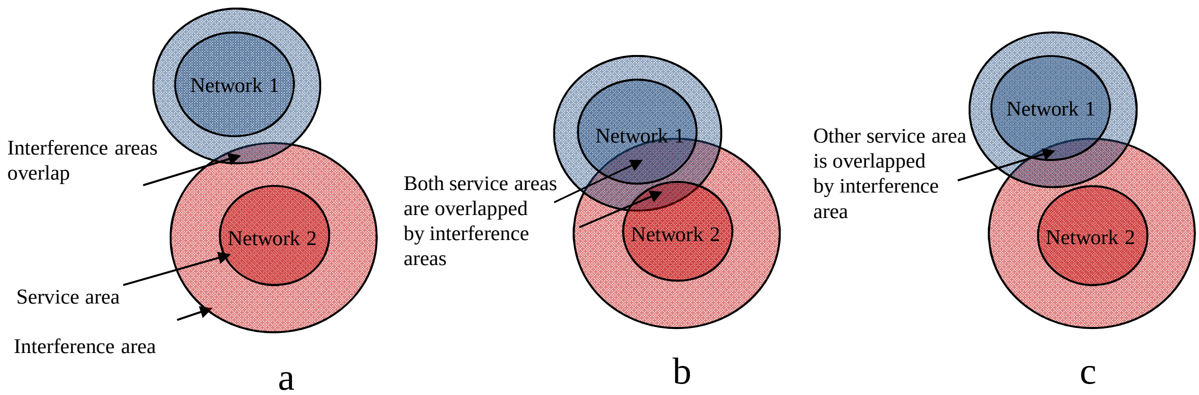


Figure 72: Networks with overlapping interference and service areas

5.2.2 Non-coordinated coexistence mechanisms

Non-coordinated coexistence does not rely on the use of a coexistence protocol i.e. no information is exchanged between systems. Instead the system attempts to adapt to or reduce interference e.g. by changing modulation, power, coding, using Carrier Sense Multiple Access (CSMA), frequency hopping. If the system determines that it is not able to operate appropriately in the current channels, it estimates whether better performance may be obtained on other channels before switching to them. In this clause the existing non-coordinated mechanisms to adapt to or reduce interference are discussed. The clauses introduce and analyse non-coordinated mechanisms which may be used to enhance coexistence in TV band white spaces.

Radio access technologies currently operating in unlicensed spectrum (ISM bands) support some forms of non-coordinated coexistence. Different radio access technologies may use different non-coordinated coexistence mechanisms and this may not enable systems with different radio access technologies to co-exist well in the same spectrum. Also, interference detection may not always be reliable even among systems with the same radio access technology, e.g. due the hidden node problem. A system experiencing interference will typically try a number of interference mitigation techniques and in parallel it may perform measurements on other available channels to evaluate their quality. If the interference mitigation techniques or channel change does not improve the performance of the system, the service failure may occur.

Some of the main interference mitigation techniques that exist are: CSMA, frequency hopping, adaptive transmissions parameters, adaptive power control, and channel switch.

- **CSMA:** The carrier sense multiple access (CSMA) mechanism is based on the principle of listen-before talk. For example, Wi-Fi uses it to allow multiple APs and stations to coexist on the same channel. A CSMA node which has data to send waits until it senses the channel as unoccupied. It backs off for a random time to avoid collisions with other CSMA nodes just after the channel becomes available, and transmits after the random backoff time if the channel is still unoccupied. If the channel is occupied it backs off again. The CSMA node increases the maximum random backoff time up to a specified limit always when the channel access fails. Each CSMA node is therefore allowed to transmit for a period of time once the medium is free, allowing a single channel to be shared in a TDM fashion between nodes associated to a single AP as well as between different APs that are sharing the same channel. The CSMA nodes back off also when they detect the channel to be occupied due the non-CSMA activity. Thus they avoid interfering non-CSMA systems.

- **Frequency hopping:** The frequency hopping is used for example by Bluetooth. In the frequency hopping, the transmissions "hop" on a set of different channels. Typically all the used channels do not have high interference level all the time, and thus at least part of the transmissions succeeds. Also, if there are multiple frequency hopping systems in the same band, the probability for two or more of them to transmit on the same channel at the same time is small. The frequency hopping system causes interference when the transmissions occur on the same channel. The enhanced version of the frequency hopping is adaptive frequency hopping. In the adaptive frequency hopping the system detects the channels which have interference (e.g. Wi-Fi) and avoid hopping on them.

- **Adaptive transmission parameters:** A system may also adapt its transmission parameters such as bit rate, modulation, coding, based on the interference level or the packet error rate. The system uses more robust transmission parameters if the interference level or packet error rate is high. The consequence may be that the transmission takes longer time, but fewer retransmissions may be needed. This mechanism is feasible if the high packet error rate is caused because of the long transmission distance or if the interference is constant. However, if the high packet error rate is caused by the collisions with other systems, the transmission parameters which cause longer transmissions may not be feasible, because longer transmissions have higher probability to collide.

- **Adaptive power control:** A system may adapt the transmission power to the interference level or the packet error rate. If the systems increase the power in a congested channel, they may cause more interference to each other and the interference may reach longer, i.e. cause interference to more systems. Thus, this mechanism may not be feasible if the interference or increased packet error rate is caused by other systems operating in the channel, but may be used if the high packet error rate is caused due the long transmission distance.

- **Channel switch:** A system constantly evaluates the quality of the channel/s where it operates. It may also evaluate the quality of the channel/s where is does not currently operate. If another channel or set of channels is evaluated to have better quality than the operating channel/s, the system may determine to change the channel. In TVWS the system may need to change channel also because of incumbent operation.

5.2.3 Coordinated coexistence mechanism

Coordinated coexistence involves the use of a protocol which one or more systems use to exchange or provide information concerning coexistence. Such information may be, for example, information on radio access technology, operating parameters, capabilities, measurement results. The information enables a coexistence function to coordinate the systems to use different channels or share the same channel. For certain radio access technologies, sharing the same channel with other systems may not be possible. The coordinated coexistence solution may enhance the coexistence of such systems by coordinating the systems to use different channels, or by coordinating the synchronization of the systems that they may share the same channel using TDM. The systems may utilize non-coordinated coexistence mechanisms while using the coordinated coexistence. Also, if the coordinated coexistence is not available, e.g. the system does not receive appropriate responses to its coexistence protocol messages within an appropriate time, it uses the non-coordinated coexistence mechanisms only.

The coordinated coexistence solution use may be organized in the following phases: initialization, discovery, connect, and information sharing. In initialization phase the network activates the coordinated coexistence use for example by transmitting a coexistence protocol message to join the coordinated coexistence. In discovery phase the coexistence set, i.e. the networks among which the coexistence coordination is needed, is discovered for the network. In connect phase the networks in the coexistence set are connected to each other, or under the same coexistence coordination. In the information sharing phase the information to coordinate the coexistence is shared among the networks within the coexistence set.

The actual coexistence coordination may depend on the radio access technologies used by the networks in the coexistence set, their methods for non-coordinated coexistence, as well as the amount of available channels. For example:

- If the number of networks in a coexistence set <= number of available channels, each network may be coordinated to operate on its own channel.
- If the number of networks in a coexistence set > number of available channels, the networks with the same non-coordinated coexistence mechanism (e.g. CSMA) may be coordinated to operate on the same channel.
- If the number of different systems which are not able to coexist well on same channel using the non-coordinated coexistence mechanism > number of available channels, frequency or time sharing considerations to share a channel between two of more systems should be taken into account in the coordination.

5.2.4 New potential coexistence mechanisms

This clause describes and evaluates potential new mechanisms which may be used for enhancing coexistence between CRSs in UHF TV white spaces.

5.2.4.1 Coexistence Gaps for coexistence between CSMA and non-CSMA systems

This clause presents a coexistence mechanism which may be applied to allow coexistence between CSMA and non-CSMA systems. This mechanism may be used in the coordinated coexistence solution.

Use of TVWS in an unlicensed fashion may result in the need for sharing of a channel between CSMA systems and non-CSMA systems. To ensure more efficient use of the channel by both systems, one potential coexistence solution is the use of gaps or periods of no transmission in the non-CSMA system. If transmission by the non-CSMA system occurs only during specific time periods (T_{ON}), while leaving periods of little/no activity to allow the CSMA system to gain access the channel. The coexistence gap will allow the CSMA system to transmit for periods of time where it experiences little or no interference from the non-CSMA system. In addition, the ability of the CSMA system to defer (due to its CSMA algorithm) to transmission during the T_{ON} period will allow for the non-CSMA system to experience little or no interference from the CSMA system. This is shown in figure 73.

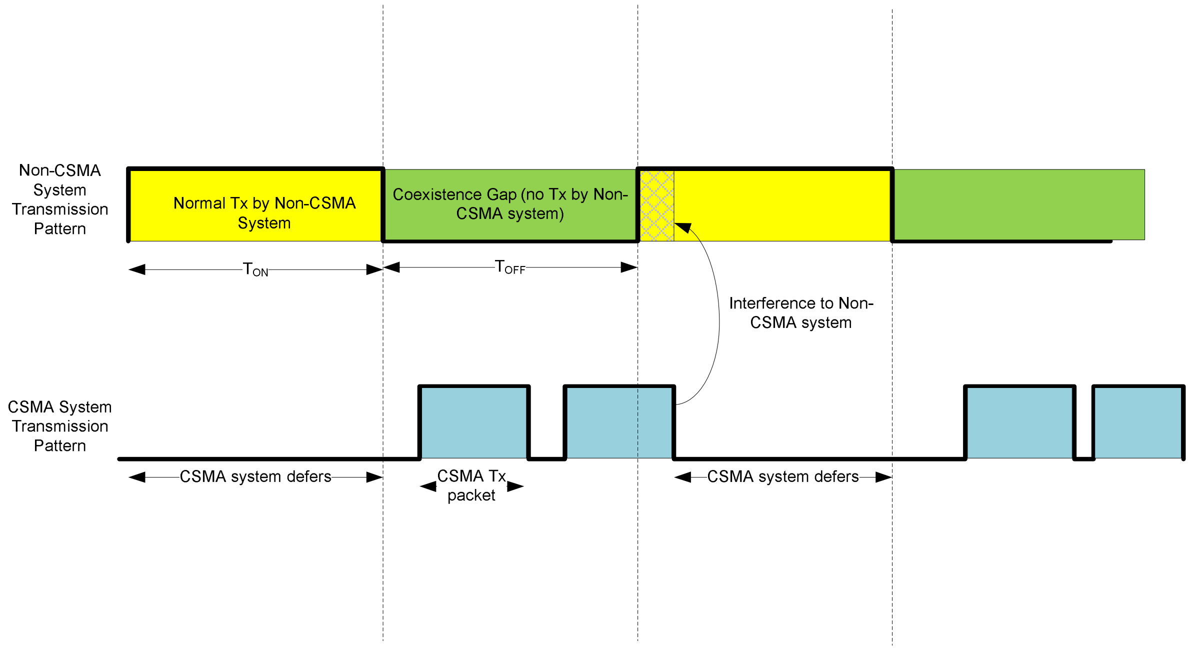


Figure 73: Use of Coexistence Gaps (CSMA system defers)

The overall efficiency of the coexistence scheme will depend on multiple factors (each highly interrelated) which include the packet length of the CSMA system, the frequency and length of the coexistence gaps, distribution of gaps, the loading of each system, the amount of traffic each system wishes to transmit at a specific time, and the relative location of the two systems. In particular, the relative location of the two systems will have an impact on whether the CSMA system will defer during the T_{ON} period. When the CSMA system is unable to sense the presence of the Non-CSMA system (e.g. detected energy falls below the CCA-ED threshold), e.g. due the hidden node problem, the CSMA system will not defer during the T_{ON} period. An example is illustrated in figure 74. For the cases where the CSMA system does not defer during the T_{ON} period, coexistence gaps in the non-CSMA system are still beneficial for the following reasons:

1) The CSMA system will have a period of time whereby its transmission is not impacted by the Non-CSMA system.

2) Due to 1), the CSMA system will likely need to send fewer retransmissions than in the case where both systems always transmit simultaneously. Thus, there may be fewer transmissions by the CSMA system which would impact the Non-CSMA system during the T_{ON} period.

3) If only some CSMA system nodes transmit during the T_{ON} period (e.g. due the hidden node problem), there will be significantly fewer transmissions by the CSMA system during the T_{ON} because most CSMA system nodes transmit during T_{OFF}.

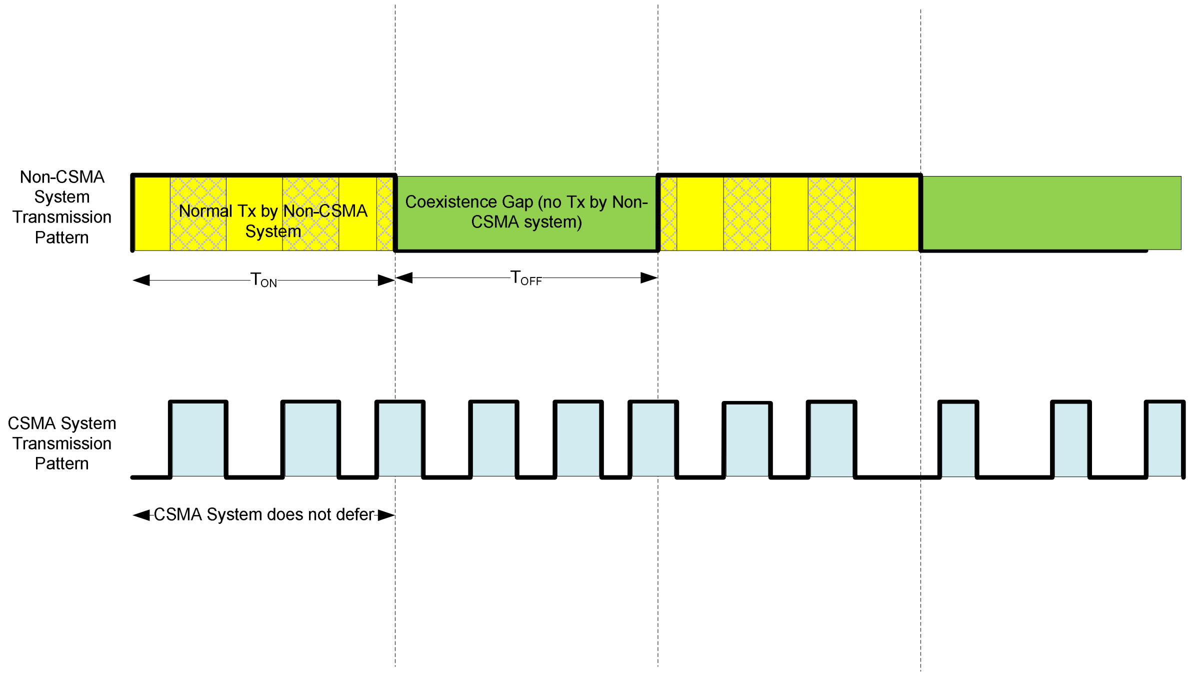


Figure 74: Interference from a non-deferring CSMA System

Based on the above discussions, non-CSMA systems which operate with regular gaps in transmission allow coexistence with CSMA systems in the unlicensed TVWS. A new RAT being developed for use in TVWS may consider built-in coexistence gaps in order to coexist with CSMA systems. Many existing non-CSMA RATs, may not be able to provide coexistence gaps due to the assumption of continuous transmission at all times. Some existing non-CSMA RATs already have mechanisms for built-in gaps in their transmission, e.g. for power savings. A CSMA system may therefore gain access to the channel during the period where the non-CSMA system is not transmitting. Knowledge that a system is able to introduce coexistence gaps could also be beneficial to the coexistence function, assuming a coordinated coexistence scheme (clause 6.2.3). If the coexistence function is aware of this, it could place the non-CSMA system supporting gaps on the same channel as the CSMA system, since these two systems would be able to coexist on the same channel.

In order to operate as a coordinated coexistence scheme (e.g. in conjunction with some type of coexistence function), the following information could be exchanged:

- The ability to provide gaps.
- The number of systems.
- The non-CSMA system would need to know whether a CSMA system was operating on the same channel:
  - If so, the non-CSMA system would operate with coexistence gaps.
  - If not, the non-CSMA system could operate without gaps.
- The periodicity and length of the coexistence gaps (or relative duty cycle of transmission to gap) would need to be communicated to the non-CSMA system so that they could be configured properly.
- The periodicity and length of the coexistence gaps could potentially also be provided to the CSMA system as well in order to allow it stop its transmission prior to the end of the coexistence gap.

5.2.4.1.1 Simulation Configuration

System-Level simulations were run using OPNET to study the behaviour of the described coexistence mechanism. Modified LTE was used as the non-CSMA system and Wi-Fi (802.11g [i.33]) was used as the CSMA system. Modified LTE means that in the simulation it was assumed that it is able to support coexistence gaps.

The system level test bench is configured as shown in table 19.

Table 19: Simulation Configuration for non-CSMA and CSMA

Parameter	Configuration
Non-CSMA	
Nodes	1 eNB, 4 UEs.
Traffic submitted	Configuration dependent, see below
Link adaptation (adaptive modulation and coding)	Enabled
Coexistence gaps	Two configurations were used: • disabled (no gaps); and • enabled, for a 50 % channel usage ratio.
CSMA	
Nodes	1 AP, 4 STA.
Traffic submitted	4,18 Mbps
Rate adaptation	Disabled
CSMA backoff	Two configurations were used: • "All defer" = all Wi-Fi nodes sense the transmission of the non-CSMA system and defer; • "None defer" = the Clear Channel Assessment Energy Detection (CCA-ED) threshold of each Wi-Fi node is set to ensure that no Wi-Fi node defers to the non-CMSA transmission. The CCA-CS (carrier sense) threshold is not modified.

NOTE: For simplicity, the simulations are configured to consider coexistence in a channel where only a single node of the non-CSMA system transmits. This allows for simpler evaluation of the results, since we do not need to consider the case where the CSMA system may defer to certain nodes but not to others.

For the "All defer" configurations, all CSMA nodes sense the non-CSMA transmission and defer. As a result, the non-CSMA transmissions experience little interference at the beginning of the non-CSMA 'on' duration (as shown in figure 73), and operate at a very high SNR.

As a reference for performance comparison, a baseline simulation was run for the non-CSMA system with no coexistence gaps on the TVWS channel, with the traffic load (submitted input data rate) to match the peak channel capacity, and with all the CSMA nodes configured to detect the transmission by the non-CSMA system and defer. A summary of the baseline and the other coexistence gap scenarios simulated is presented in table 20.

Table 20: Coexistence Simulation Scenarios

	Non-CSMA System	CSMA System
Baseline	• No coexistence gaps • Traffic Load = 100 % channel capacity • Full Buffer = Yes	All defer
Case 1	• Coexistence Gap, channel usage ratio set to 50 % • Traffic load = 50 % channel capacity • Full buffer = Yes	All defer
Case 2	• No coexistence gap • Traffic load = Same as Case 1 • Full buffer = No	All defer
Case 3	• Coexistence Gap, channel usage ratio set to 50 % • Full buffer = Yes	None defer (does not defer to non-CSMA)
Case 4	• No coexistence gap • Full buffer = Yes	None defer (does not defer to non-CSMA)

It should be noted that the configurations "All defer" and "None defer" are ideal; it is expected that in real deployment scenarios, a mix of CSMA nodes is encountered (some nodes defer, some nodes may not). The reason for using this ideal configuration is to find upper and lower bounds of the performance.

The simulation results are shown in the following clause.

5.2.4.1.2 Simulation Results

The throughputs of the non-CSMA system in the TVWS channel in the baseline case (no interference, no coexistence gaps (CG), and full buffer), together with the throughputs for both systems for cases 1 and 2, are shown in figure 75.

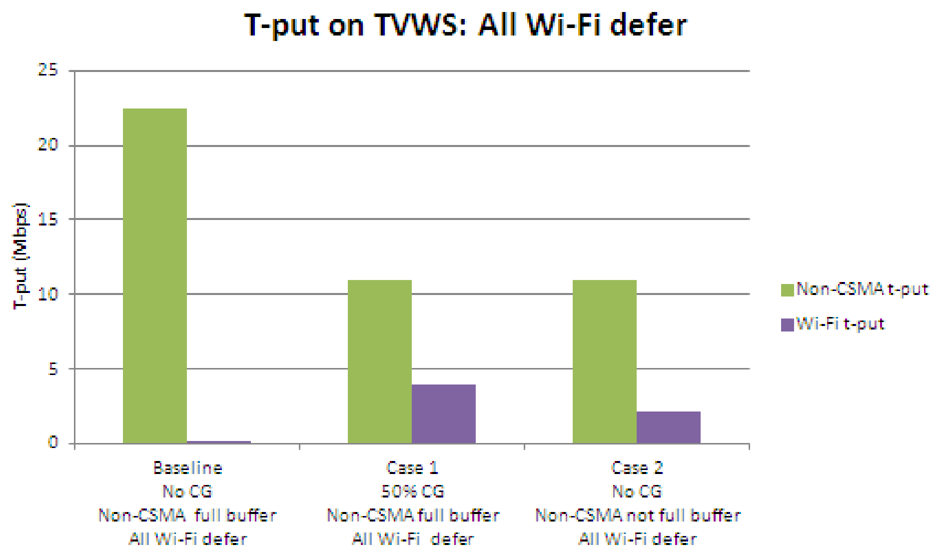


Figure 75: Measured throughputs for the "All defer" case

From the figure above, it can be seen that in Case 1, when coexistence gaps (with 50 % channel usage ratio) are allocated by the non-CSMA system, the measured throughput for the CSMA system is equal to the submitted load (4,18 Mbps). For Case 2 however, when no coexistence gaps are scheduled, the CSMA system suffers due to the interference with the non-CSMA system, and the CSMA throughput decreases. Note that the non-CSMA system throughput performance in Case 2 is the same as for Case 1, and is equal to 50 % of the channel capacity (which equals the submitted traffic load - see table 2).

Figure 76 shows the throughputs for the two systems for Cases 3 and 4, respectively, when none of the CSMA nodes defers to non-CSMA transmissions (corresponding to the non-deferring case in figure 73). Here, due to interference from the CSMA, the allowable throughput of the non-CSMA system obtained assuming full-buffer decreases in the Case 4 where there are no coexistence gaps (relative to the Case3 where there are coexistence gaps) and the CSMA throughput goes to zero in Case 4.

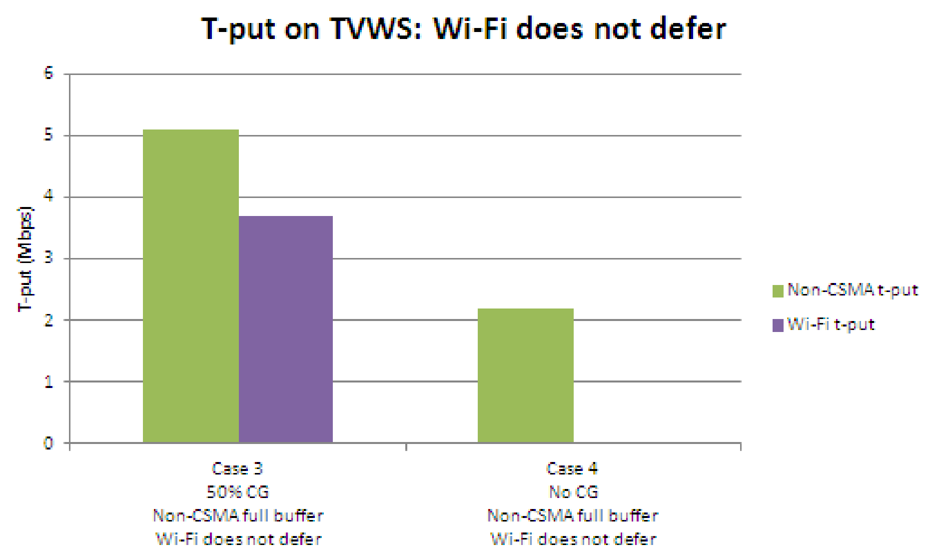


Figure 76: Measured throughputs for the "None defer" case

Based on the simulation results presented above, the following observations can be made regarding the performance.

- CSMA system performance:
  - If the CSMA nodes defer to non-CSMA system, and a 50 % coexistence gap is used by the non-CSMA system, there is no performance degradation in the CSMA system compared to its offered traffic load. If however, the non-CSMA system does not use coexistence gaps to transmit the same load, the CSMA system performance degrades by a factor of 2 with respect to its offered traffic load.
  - If the CSMA nodes do not defer to the non-CSMA system, the CSMA system experiences a minimal performance degradation when a 50 % coexistence gap is used by non-CSMA system (Case 3) compared to the offered CSMA traffic load that is achieved in Case 1. If the non-CSMA system does not use coexistence gaps and its traffic is full buffer, the CSMA throughput becomes almost zero (Case 4). This is because in Case 4, the CSMA system's transmissions always experience interference, and no rate adaptation is modeled in the test bench for the CSMA system. It is expected that if rate adaptation would be implemented, the CSMA system throughput in Case 4 would be non-zero, but would still be smaller than for Case 3, since interference caused by the non-CSMA system would degrade the channel conditions for the CSMA system.
- Non-CSMA system performance:
  - If the CSMA system nodes defer to the non-CSMA system, there is no performance degradation for the non-CSMA system with respect to its submitted load, regardless of the coexistence gap (Case 1 and Case 2). This is expected, as in both cases, the two systems never transmit at the same time.
  - If the CSMA system nodes do not defer to the non-CSMA system transmission, when a 50 % coexistence gap configuration is used (Case 3), the non-CSMA system performance degrades by a factor of 2 with respect to Case 1(CSMA nodes defer). This is expected, and is due to the interference generated by the CSMA system nodes. It is interesting to note however, that when the non-CSMA system does not use coexistence gaps (Case 4) and the CSMA system does not defer, the non-CSMA system performance degrades by a factor of 5 with respect to Case 1 (coexistence gap, CSMA nodes defer), which illustrates the potential benefit of coexistence gaps for the non-CSMA system, even in the interference scenario depicted in figure 73. Note that although the non-CSMA system transmission is interfered by the CSMA system transmission, the non-CSMA throughput does not drop to zero in Case 4 because adaptive modulation and coding was implemented for the non-CSMA system in the test bench.

The simulation results presented above suggest that it is beneficial for a non-CSMA system to configure coexistence gaps, even for scenarios where the CSMA system does not defer. It should, however, be considered that several limitations and assumptions were used to simplify analysis. In particular, it is assumed that only a single node transmits in the non-CSMA system. A non-CSMA system where multiple nodes can transmit would add an additional degree of difficulty because the ability of a CSMA system sense interference and thus to defer to several different nodes of the non-CSMA system would need to be considered, and the throughput in both DL and UL would need to be analysed as well. It should also be noted that these simulation results do not qualify the relationship between throughput and other affecting factors such as packet length, coexistence gap length and frequency.

5.2.4.1.3 Example Implementations for Coexistence Gaps

The simulation results above show the coexistence performance for a CSMA and non-CSMA system when the non-CSMA system is LTE and the CSMA system is Wi-Fi. The simulation platform was developed using LTE-FDD (DL-only) and the coexistence gaps were created by the absence of any transmission in consecutive subframes in order to create the coexistence gaps. Also, a coexistence gap length of 5 subframes was used in the simulations (T_{ON} = 5 ms and T_{OFF} = 5 ms), which was achieved in FDD by simply having the scheduler not schedule downlink resources during the gap period, as well as the absence of any reference signals during this period (to which the UEs are made aware). Such a method is applicable for FDD only. The following clauses present possible example implementations for coexistence gaps which could be used in the case of TDD.

It may also be beneficial to change the length of the coexistence gap (or the duty cycle as defined in this clause) based on the loading of the systems. For instance, an LTE system with a higher load could decide to allow for less time for Wi-Fi transmission by reducing the gap time and using a duty cycle of 80 %. Since the packet lengths for most Wi-Fi systems typically range from 100 µs - 400 µs (including the channel sensing time), a gap with even a single LTE subframe is in theory sufficiently long to provide minimal Wi-Fi transmission. This also means that an LTE system may implement coexistence gaps with a particular duty cycle in a non-contiguous fashion (multiple periods of T_{ON} and T_{OFF} in a given frame). However, as the amount of consecutive gap time decreases, the relative interference between Wi-Fi and LTE at the end of the gap will increase. For this reason, it is preferred to keep the gaps as contiguous as possible. This goal may be more challenging depending on which of the methods is selected below.

The implementations given below are examples only and other options are also possible. While more detailed simulations to measure the performance of such methods in terms of factors such as latency would be required, such studies would be more appropriately performed in 3GPP. In particular, issues related to reduction in CQI measurements, for example, and the resulting impact on LTE performance would need to be evaluated. Also, the coexistence gap mechanism may only be feasible when a single non-CSMA system operates in a given channel. However, issues as to how adjacent cells and eNBs coordinated the gaps they used would also need to be addressed. In addition, mechanisms for signalling of the actual gap configuration to the UEs in each of these mechanisms (e.g. RRC messages), would also need to be developed. Finally, each of the method below may result in a given number of changes to the existing LTE RAT (both signalling and procedures).

Use of MBSFN Subframes Combined with non-Scheduled UL Subframes

Coexistence gaps may be created by having the eNB schedule MBSFN (Multicast/Broadcast over Single Frequency Network) subframes for this purpose, in combination with UL subframes which are not scheduled by the eNB for UL transmission (and therefore become part of the gaps themselves). In Rel-8/10, MBSFN subframes are used for, among other things, to transmit the Multicast Channel (MCH) and during the transmission of MCH in the MBSFN subframes, the eNB will not transmit any other downlink transport channels.

The LTE system can create coexistence gaps by scheduling MBSFN subframes and not using them for MCH. This leaves these subframes empty except for the first two OFDM symbols of PDCCH (the non-MBSFN portion). In order to have significantly large coexistence gaps to allow for WiFi to access the channel and transmit with little or no interference from LTE, the eNB can use multiple consecutive MBSFN subframes and the resulting coexistence gap will therefore consist of the totality of all of these MBSFN subframes. For TDD, the allowable subframes for definition of MBSFN subframes are subframes #3, 4, 7, 8 and 9. However, in a given TDD UL/DL configuration, if any of these subframes is actually an UL subframe, the coexistence gaps can be defined by not scheduling UL transmission for any UEs in these subframes.

Depending on the TDD UL/DL configuration, the potential subframes for MBSFN may be predominantly UL subframes. As a result, the coexistence gaps implemented using this method would severely decrease the amount of UL traffic for specific TDD UL/DL configurations, thus making the system inefficient when there is a large number of UEs. Such an issue is not present in the subsequent methods, whereby the relative number of UL and DL subframes can be kept constant (or approximately constant) by the introduction of coexistence gaps.

Fixed Frame-Based Coexistence Gaps

Another method to introduce coexistence gaps in LTE-TDD with a minimal impact on HARQ and other transmission timing rules would be to have the gaps span over an entire frame or an integer number of frames. Because the TDD UL/DL configuration is repeated each frame, a gap which spans over an entire frame or an integer number of frames makes it easier to adapt the timing and rules of the TDD HARQ and other operations that depend on the UL/DL relation in such a way that the all HARQ timing is delayed by exactly the number of frames in the coexistence gap. As a result, the proposed approach would be to use the existing HARQ rules for the timing of grants, transmissions, and acknowledgements, with the added condition that HARQ timers are frozen on frames which make up the coexistence gap.

During a frame used for coexistence gaps, the eNB will not transmit any signals on the channel for the entire frame. As a result, the UE will not try to decode control or reference signals, or transmit in the UL. The eNB will signal the pattern and frequency of the frames used for coexistence gaps to the UEs (e.g. using system information), so this information is known by all UEs during operation. The UE follows HARQ timing rules and measurement timing rules defined in Rel-8, except that the timing will be frozen during the frame used for coexistence gaps.

Since the consecutive gap time for this method is the longest among the three methods presented in this clause (an entire LTE frame), it is expected to yield the best performance in terms of coexistence between LTE and Wi-Fi.

Fixed Subframe-Based Coexistence Gaps

One approach for creation of coexistence gaps is to define these gaps as a collection of blank subframes. These blank subframes consist of either UL or DL subframes where neither the eNB nor any UEs under the control of the eNB will transmit. For downlink subframes, such a blank subframe will contain no physical control or data channels and no downlink reference symbols. As a result, all UEs under the control of an eNB are made aware of the presence of such blank subframes. For uplink subframes, no UEs will be allowed to transmit on blank subframes. Each TDD UL/DL configuration is then modified to introduce regular blank subframes so that the new configurations allow existing PHY procedures (e.g. HARQ, transmission of system information, etc) for TDD-LTE to be performed with minimal impact, and to allow sufficient length gaps for Wi-Fi systems coexist on the same channel. For instance, blank subframes can be selected so that they eliminate certain HARQ processes but maintain the UL and DL subframes required for other HARQ processes to be used with the current LTE-TDD HARQ timing.

The selection of the appropriate method would depend not only on the coexistence performance (how well Wi-Fi and LTE coexist) and the impact on performance of each of these RATs on their own, but also on the extent of the changes to the LTE RAT which would be required. While the use of MBSFN for implementing gaps has little change to existing LTE procedures (except for potential new signalling between eNBs and from eNB to UE), the other mechanisms may require some LTE procedural changes. The significance of such changes would need to be evaluated during detailed specification of any of these methods, as well as in selecting the preferred method.

6 Device classes

This clause describes the potential device classification for the devices operating in UHF TV band white spaces. The potential device classes define the technical characteristics of WSDs, for instance their emission characteristics, operation range, and other technical parameters. The WSDs have different characteristics as they may support different radio standards, have different roles in the wireless networks, and as their radio implementations may vary depending on the cost and purpose of the device. The device classification enables defining different requirements to the WSDs which have different characteristics. For example all WSDs may not be required to query the geo-location database. Also, the information that the WSDs are required to provide may depend on the device classification.

The current work on the UHF TV white space regulations provides some examples for the possible device classification. The FCC and CEPT considerations are summarized as background:

The current FCC rules [i.1] categorize the WSDs in the following classes:

- Fixed device - maximum EIRP 4 Watts. Device is restricted from operating at locations where height above average terrain of the ground level is greater than 76 meters. Fixed device is required to register its operations in the geo-location database.
- Personal/portable devices:
  - Mode II - maximum EIRP 100 mW (40 mW on first adjacent channel to an occupied TV channel). Mode II device relies on geo-location and database access to determine available channels at its location on a daily bases and if it has moved.
  - Mode I - power limits are the same as for Mode II. Mode I device operates only on channels identified by either a Fixed device or Mode II personal/portable device.
  - Sensing-only device - maximum EIRP 50 mW. Sensing-only device relies on spectrum sensing without the use of geo-location and database access.

The current CEPT approach proposes location specific output power levels for WSDs. Thus the device classification in Europe may differ from the FCC device classification. The ECC report 159 [i.3] leaves the device classification for future standardization, but gives some indications to the information which may be considered in device classification: antenna parameters such as antenna type, antenna height, type of technology and modulation, power, and mobility. Different classes can exhibit different interference characteristics allowing different EIRP limits, for example devices with good out-of-band emission characteristics may be allowed to transmit with higher power levels on some frequencies and/or locations. Even if the device classification is left for future, the report defines some device categorization:

- Personal/portable device - device can be carried by individual users, e.g. mobile phones, personal media players, laptop computers. Operation height 1,5 m assumed in protection study in the report, but device may appear at other heights, e.g. in a building/balcony.

- Home/office device - non-portable device, such as WSDs built in flat panel TVs, personal video recorders and other devices, which are designed to remain primarily in one place. Operation height 10 m - 30mm assumed in protection study in the report.

- Private/public access points - expected to be fixed in position and typically located where connection to a backhaul network is available. Within the coverage of a private/public access point, other categories of WSD may be used. Example of a private access point is e.g. a Wi-Fi access point operating in UHF TV band white spaces. Public access points may provide Internet access on higher transmission power e.g. in rural areas.

In addition, the report assumes that a WSD may act as a proxy for the database queries for another WSD or a set of other WSDs. The querying WSD is called the master WSD and the WSD(s) it does the query for is called slave WSD(s). The master WSD would ensure that the slave WSDs operate according to the constraints returned by the database.

6.1 Classification based on WSD role in operation enablement

Master-slave topology is commonly used in many communication networks. The master has the control over one or more slave devices. It may determine the operating frequencies and operating timeslots for the slave devices. Such master-slave networks may be formed around base stations, access points, or between terminals on ad hoc basis. There is also wireless communication which does not follow the master-slave topology. Devices may provide broadcasting service, they may form mesh networks, and peer-to-peer links. In such scenarios, one device does not control the other devices in the network, at least all the time. The WSDs operating in UHF TV band white spaces may also support various networking topologies and scenarios. The WSD requirements and classification should support such flexible operation.

This clause introduces device categories based on the WSD role in operation enablement:

- Devices which access the geo-location database to get the enablement for the operation in UHF TV white spaces:

    - DB-enabled master.

    - DB-enabled stand-alone.

- Devices which get the enablement for operation from another WSD:

    - WSD-enabled device.

The *DB-enabled master* and *WSD-enabled device* correspond to the Mode II and Mode I devices based on the FCC rules [i.1], and the master and slave indications in the ECC report 159 [i.3]. However, the terms used by the FCC are not very descriptive, whereas the terms master and slave are closely tied to a specific network topology only. Thus, different terms are used in this clause. The *DB-enabled stand-alone* is a new type of device category.

The *DB-enabled master* queries the geo-location database to access the spectrum availability information (e.g. available channels and allowed EIRP for those channels). It is authorized to provide the spectrum availability information to other devices within its service area. The service area is the area that the device can reach with the transmission output power allowed to it. The *DB-enabled master* is not necessarily the master of a wireless network enabling only the operation of slaves in the network. It may provide the enablement to any device in the service area.

The *WSD-enabled device* operates in the service area of a *DB-enabled master*, which provides the enablement for the operation. The *WSD-enabled device* should connect to a *DB-enabled master* to get the enablement, and after that regularly receive an enabling signal from the *DB-enabled master* to validate the enablement. If the *WSD-enabled device* fails to receive the enablement signal within a specified time, it is not allowed to continue its operation. This may occur for example if the *WSD-enabled device* moves outside the service area of the *DB-enabled master*.

The *DB-enabled stand-alone* is a device which queries the geo-location database to access the spectrum availability information, but which is not authorized to provide the information to other devices within its service area. This device may be broadcast-only WSD. The geo-location database should be able to estimate the potential interference area of a WSD network before it provides the spectrum availability information to the WSD. As the *DB-enabled stand-alone* device does not enable the operation of other WSDs, its potential interference area is smaller than the potential interference area of a *DB-enabled master* if both WSDs operate with the same transmission output power. Thus, the available spectrum information may be different for these WSDs at the same geo-location. As an example, the *DB-enabled stand-alone* may be allowed to operate on higher transmission output power. Figure 77 illustrates the potential interference areas of *DB-enabled master* and *DB-enabled stand-alone* device, which have the same transmission output power.

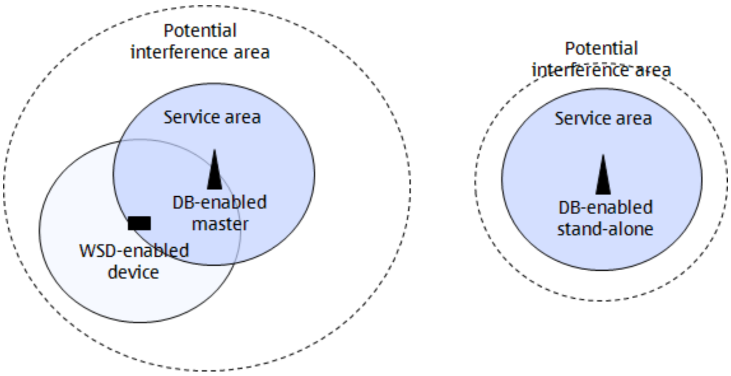


Figure 77: Potential interference areas for DB-enabled master and DB-enabled stand-alone device operating with the same output transmission power

Besides being a broadcast-only device a *DB-enabled stand-alone* device may connect to other devices which have received the enablement for their operation by themselves, e.g. by accessing the geo-location database. For instance when some WSDs form an ad-hoc network locally, or when two high power WSDs are connected to each other.

If the same channel is not available at the geo-locations on both WSDs, the WSDs may transmit on different channels. As an example, a WSD may transmit on a channel with high transmission output power, but using the same channel for transmissions at the geo-location of another WSD with the needed transmission output power may not be allowed. In this scenario the used radio technology and the WSDs should support transmission and reception on different channels. The scenario is illustrated in figure 78: both WSDs access the geo-location database to query the spectrum availability information at their geo-locations. WSD1 is allowed to transmit on channel X and WSD2 is allowed to transmit on channel Y.

If a same channel is available at the geo-locations of both WSDs, the WSDs may transmit on the same channel. In some areas there may only be one channel available, and the WSDs will transmit on the same channel. In such scenario the used radio technology and the WSDs should support transmission and reception on the same channel.

According to such scenarios, the radio system should support connection setup which enables setting up both FDD and TDD operation between *DB-enabled stand-alone* devices, because the operation mode may depend on the spectrum availability at both ends. The connection may be setup e.g. using out-of-band mechanisms.

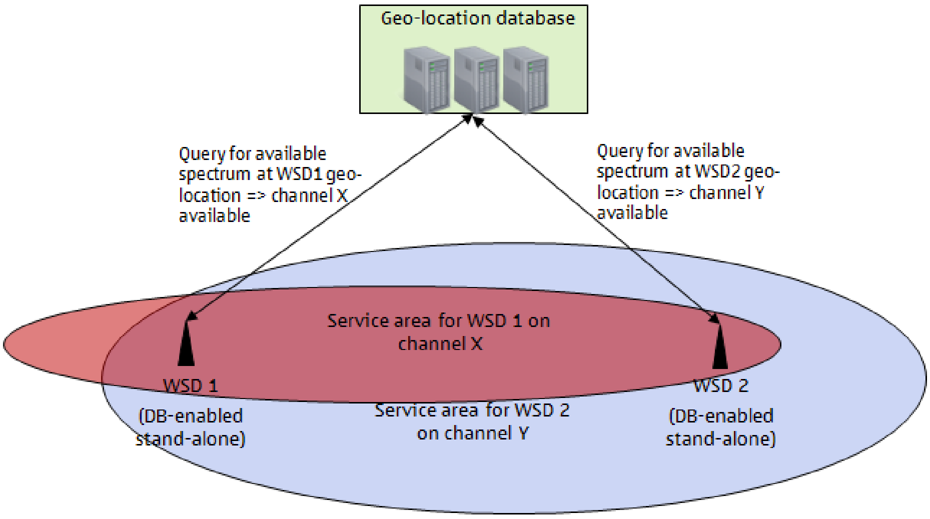


Figure 78: Example of the communication between DB-enabled stand-alone devices

6.2 WSD parameters to geo-location database

This clause defines a set of WSD parameters that a geo-location database may use to estimate the interference that the WSD may cause to the primary user, and - based on that - to calculate the available spectrum (i.e. available channels and allowed transmission output power) for the WSD itself. The clause also introduces a possibility for WSD to provide a flexible set of parameters to the geo-location database. The more information the WSD is able to provide, the more accurately the geo-location database is able to calculate the available spectrum for the WSD, if it is assumed that the geo-location database is able to use all the provided parameters. However, different WSDs may also have different capabilities to provide information, e.g. portable WSDs may not be able to provide antenna height and direction accurately. The WSD should only be allowed to provide reliable parameter information to the geo-location database. There are many parameters which affect the estimation of the interference that the WSD may cause, such as:

- Transmission output power.
- Bandwidth.
- ACLR/spectrum mask.
- Indoor/outdoor.
- Geo-location and accuracy.
- Mobility.
- Antenna height, direction, angle, and accuracy of them.
- Receiver sensitivity.
- Existence of enabled-WSD devices (e.g. slaves) in the network and their parameters.

As a general approach, a set of parameters may be defined in a basic device class and further parameters can be provided in addition to such class. The purpose of this clause is not to define the classes but to list different parameters to derive the WSD interference characteristics. In future the parameters could be grouped in classes (e.g. mandatory parameters) or considered as additional parameters (e.g. optional parameters).

In the case a WSD provides only a few parameters (e.g. basic class which may be defined through WSD's ACLR parameter, and WSD geo-location information), the geo-location database is only able to roughly estimate WSD potentially caused interference, since it should use many default values in the estimation. In this case the available spectrum and transmission output power allowed for WSD would be smaller as the complete set of WSD parameters allowing a more accurate estimation is not available.

If the WSD is able to provide additional parameters based on which the geo-location database can estimate the potential WSD interference more accurately, then a more accurate available spectrum as well as a more accurate transmission power for the WSD can be calculated. However, depending on the geo-location database implementation, taking the additional parameters into account may require more processing, and the database may not be able to provide the response immediately. For example, due to the WSD mobility, an immediate response for the database query may be an important factor, in which case the WSD might only provide a minimum set of information (e.g. basic class). In case of no mobility, transmission output power and bandwidth may be the most important factors for a WSD, in which case the WSD might also provide additional parameters to the database. Some examples of WSD parameters, which affect the WSD potentially caused interference estimation, are described below.

WSD ACLR

This parameter defines the very basic interference characteristics of the WSD. A set of ACLR values may be predefined in ACLR classes. If the DB-enabled device enables other WSDs within its service area, the ACLR is assumed to be the same for all the enabled devices, i.e. the ACLR may depend on the radio technology.

WSD geo-location

This parameter defines the geo-location of the WSD. Typically the information would be the actual geo-location of the device, but in some cases the device may be interested to query information related to another geo-location, e.g. before it changes its position.

Typically the geo-location would be defined by the geo-location of the DB-enabled device. The WSD-enabled device may be allowed to operate with the transmission output power which is the smallest of:

- The transmission output power that is allowed for the DB-enabled master.
- A predefined maximum power for the WSD-enabled device (this applies if the DB-enabled master is allowed to operate with high power).

If the DB-enabled master is allowed to operate with higher power than the predefined maximum for WSD-enabled device, and it wishes to enable some WSDs to operate above the predefined transmission output power, it may provide the geo-location of those WSD-enabled devices to the geo-location database.

WSD geo-location method/accuracy

This parameter indicates the accuracy of the WSD geo-location. The devices may use different methods (or a combination of them) to calculate their geo-locations, e.g. GNSS, WLAN ID, Cell ID. Also, the geo-location may be configured in the non-moving WSD when it is installed. The geo-location method affects the geo-location accuracy. The regulations may define a minimum requirement for the required accuracy for WSD, according to which the geo-location database is still able to evaluate the potentially caused interference of the WSD.

WSD role in enablement

This parameter defines whether the DB-enabled device acts as a DB-enabled master or stand-alone device. If the information is not provided, the geo-location database assumes that the device is DB-enabled master, because the interference area of DB-enabled master is larger than the interference area of DB-enabled stand-alone, as presented in clause 6.1.

WSD height and accuracy

These parameters define the WSD height information (e.g. physical antenna height plus the ground relative height). All WSDs may not be able to calculate their height information, e.g. a portable or mobile WSD may not know whether it resides in the lower or higher floors of an apartment building. However, if a WSD knows its height information, it may provide the information to the geo-location database. There may be minimum requirements for antenna height accuracy, which the WSD providing the antenna height information should meet.

WSD antenna angle, antenna direction and accuracy

These parameters define the direction where WSD causes interference. If the WSD is capable of determining its antenna angle and direction, it may provide the parameters to the geo-location database. If the parameters are not provided to the geo-location database, the GLDB may assume an omni-directional antenna.

These parameters may significantly affect the spectrum resources allowed for the WSD. An example of this scenario is presented in figure 79**.** It compares a device transmitting with omni-directional antenna (blue) and directional antenna (red). The existence of incumbent user (white) may limit the transmission of the omni-directional antenna more than the transmission of directional antenna, if the directional antenna is not directed towards the incumbent user. This example scenario considers only the DB-enabled stand-alone devices, e.g. the broadcast scenario. In case of a master-slave scenario, the DB-enabled device may also provide the antenna angle, direction, and accuracy parameters of the WSD that it enables if they are known.

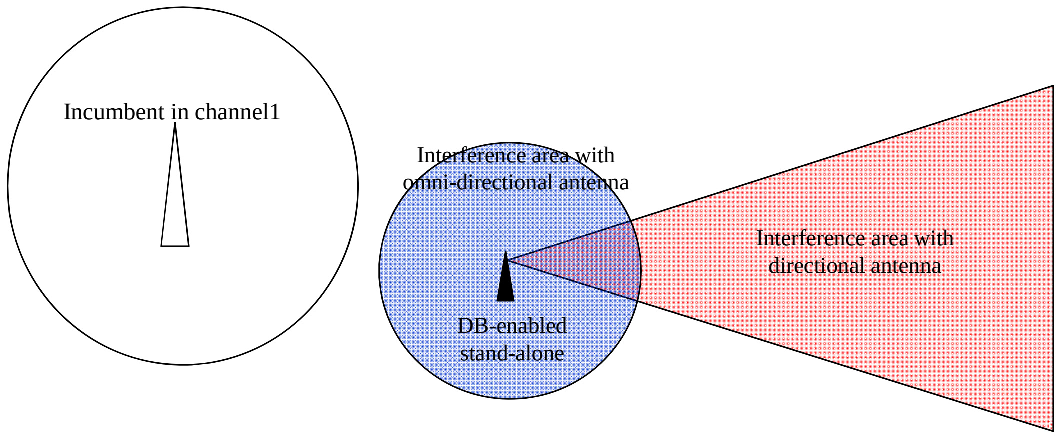


Figure 79: Example of interference areas with omni-directional and directional antenna transmissions

There may be minimum requirements for antenna angle and direction accuracies, which the WSD providing the antenna angle and direction information should meet.

Indoor/Outdoor

This parameter defines whether the WSD operates indoor or outdoor. If the WSD knows whether it is operating outdoors or indoors, it may provide the information to the geo-location database. The geo-location database can take the information into account in the propagation algorithms.

WSD Receiver sensitivity

This parameter defines the WSD receiver sensitivity. The minimum requirements for the receiver sensitivity are typically defined for a radio technology, but sensitivity can also vary according to the implementations. If bi-directional wireless communication between DB-enabled master and WSD-enabled device is required at least for the enablement, the device with the worse sensitivity limits the link distance. If the information is not provided, the geo-location database may assume good sensitivity, because good receiver sensitivity in both ends of the link increases the link distance, and may enlarge the potential interference area.

WSD Operation area (relates to mobility)

This parameter may be given, e.g. as multiple geo-locations or distance from the geo-location. The DB-enabled device may provide area information to the geo-location database to request the spectrum availability information (e.g. channels, transmission output power) which is valid for the whole area. As an example a mobile WSD may be interested to receive information for larger area, even if the available spectrum for the larger area may be more limited. Then, the WSD does not re-query or change its operating parameters frequently while moving.

WSD Capability to limit ACLR

This parameter relates to enhanced capabilities of the WSD. The WSD may support features, e.g. spectral pre-coding, which enable it to limit the ACLR. The DB-enabled device may provide the limitation capabilities to the geo-location database. It should also provide the information, whether the limitation is used in downlink, up-link or both.

Annex A: Definition of interfere-victim reference point [i.3]

The selection criteria of interfere-victim reference point are one of the important things to calculate the maximum transmission power allocation for multiple WSDs.

If one considers the multiple in-block/out-of-block interference effects from neighboring WSDs, only one selection criterion, which is to choose the closest point for each WSD in the protected contour of the incumbent service as shown in figure A.1, could be considered.

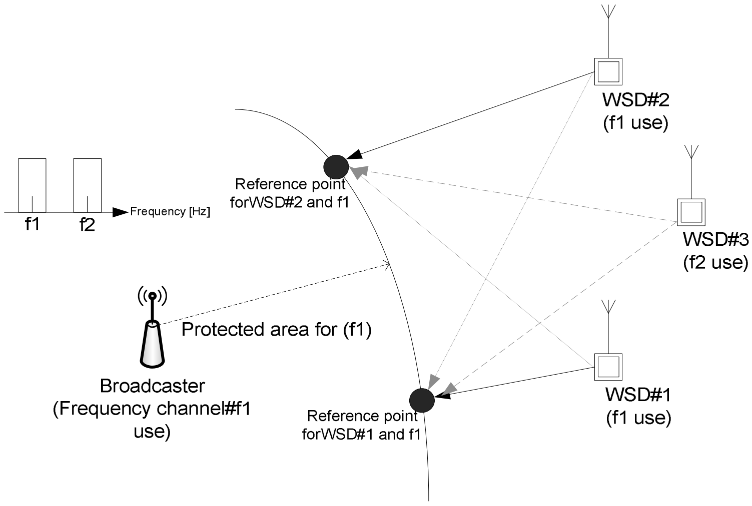


Figure A.1: Selection Criterion of The Interfere-victim Reference Points for The Maximum Power Allocation for Multiple WSDs

Annex B: UL Data channel performance of LTE system Operating in Channels Adjacent to DTMB

B.1 Coexistence scenario

A set of research projects on cognitive radio (e.g. i [i.24]) mentioned that LTE systems with cognitive ability opportunistically using the UHF TV band is a typical use case. If the devices of the LTE system have the ability to change their RF parameters to avoid interference to the TV system, as well as obey the regulatory instructions, the LTE system may have the chance to use the un-vacated TV white space channel. However, the LTE system should protect itself when utilizing the white space channel because the interference from a TV system may also be serious.

Besides the DVB-T scheme, it should be noted that in different regions there are some other digital television standards which need to be taken into account in the coexistence studies in UHF bands. Digital Television Terrestrial Multimedia Broadcast (DTMB) systems developed in the People's Republic of China have been used in mainland China, Hong Kong, and Macau, and also received strong interests from other countries.

Figure B.1 shows this coexistence scenario based on which some organizations (e.g. [i.24] and [i.25]) have already done research on coexistence between LTE systems and TV broadcast systems. In figure B.1, the distance d between the base station of DTMB and the BS of a TDD-LTE-CR is defined as the isolation distance. As indicated in [i.26], that means the CR system should be located beyond a specific isolation distance to use TV white space frequency without being interfered by a DTMB system. DTMB occupies one 8 MHz channel while LTE-CRS under macro deployment occupies one 5 MHz channel configured at the adjacent channel or second adjacent channel. The configurations of the LTE channel being considered are illustrated in figures B.2 and B.3. It should be pointed out that this doesn't mean that using LTE-CRS in TV white space under a macro cell deployment is the most applicable scenario, but just one of the options based on which we conduct the study to show the influence to CR systems when utilizing TV white space channels. The simulation parameters which are described below are used for this simulation purpose only. They do not indicate any specific implementation for LTE-CRS operating in TV white space.

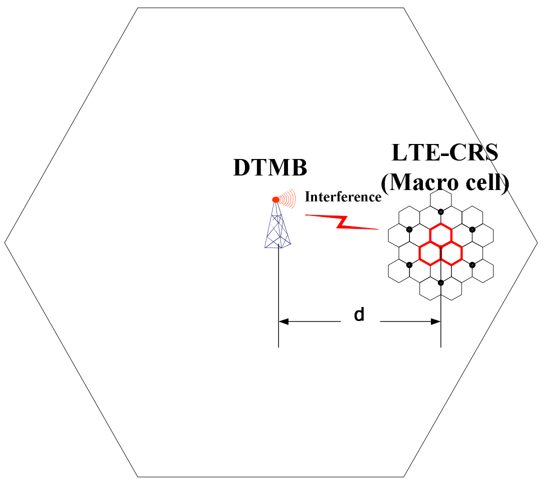


Figure B.1: Coexistence scenario

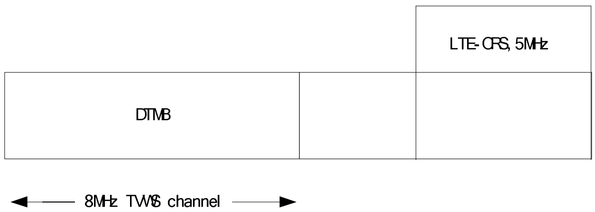


Figure B.2: Adjacent channel coexistence channel configuration for DTMB and LTE system

Figure B.3: Second adjacent channel coexistence channel configuration for DTMB and LTE system

Space isolation and frequency isolation are utilized as two common coexistence methods. The former represented by isolation distance takes advantage of propagation loss to decrease the interference power at the receiver of the interfered system; and the latter represented by ACIR mitigates the interference using the device's RF capabilities. ACIR is determined by adjacent channel leakage power ratio (ACLR) and adjacent channel selectivity (ACS) of which the requirements are defined by the standards. Based on the current standard specifications of LTE [i.17] and DTMB RF parameters, and following with the calculation method in [i.27], the LTE-CR BS ACS and DTMB ACLR of the above channel configuration are calculated and listed in table B.1.

For a given ACIR, the isolation distance should be the crucial factor to guarantee the performance of the TDD-LTE system. In the following clause, we will investigate the relationship between the system performance loss and isolation distance, then try to find the available area where the LTE-CR system could coexist with DTMB system.

Table B.1: ACLR and ACS requirements based on current standard specification

		Adjacent channel	Second adjacent channel
DTMB system	ACLR	75 dB	89 dB
BS of LTE-CR system	ACS	49,9 dB	54,3 dB

B.2 System simulation

Throughput loss is used as the metric to measure the degradation of the TDD-LTE-CR performance. In thisclause, different levels of throughput degradation result in a required corresponding isolation distance. Monte Carlo system simulations have been run as follows: First, selecting the frequency relation between DTMB and TDD-LTE-CR, for example, if the channel configuration is adjacent channel coexistence, then the ACLR and ACS value are set accordingly; then the isolation distance defined as the distance between the base station of the DTMB and the BS of the TDD-LTE-CR is gradually increased until the throughput loss satisfies the anticipated value. That resulting distance is the isolation distance to guarantee such system performance. For each distance, more than 1 000 snapshots will be performed to achieve the average throughput loss.

The spectrum mask and vertical attenuation pattern of DTMB in China are shown in figures B.4 and B.5. Tables B.2 and B.3 illustrate the other parameters related to this simulation in accordance with the deployment parameters of current DTMB and TDD-LTE systems. It is noted that Recommendation ITU-R P.1546-4 [i.6] is chosen as the propagation model as it models well the propagation in UHF frequency band. Thus the path loss is affected by transmitting distance, height of transmitter and receiver's antenna, the radio environment and so on.

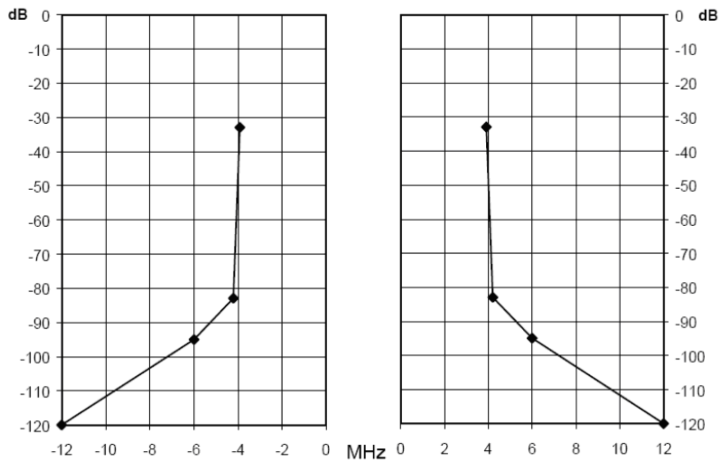


Figure B.4: DTMB Spectrum Mask [i.25]

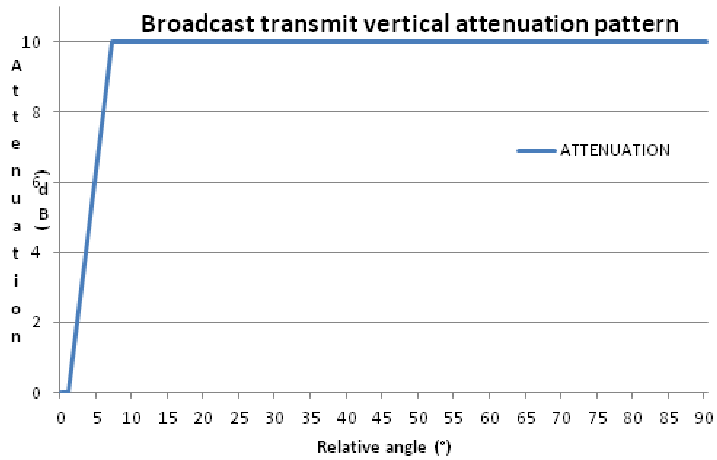


Figure B.5: Vertical attenuation pattern of DTMB transmitting antenna [i.25]

Table B.2: Parameters of DTMB system

DTMB system	
ERP (KW)	1
EIRP(dBm)	62,15
Frequency (MHz)	698
Bandwidth（MHz）	8
Height of transmitter antenna (m)	150
Antenna direction figure(Horizontal)	Omni directional
Down-tilt of transmitter Antenna	0°
Height of receiver antenna (m)	10
Gain of receiver antenna(dBi)	14,15
Feeder loss of receiver antenna(dBi)	5
Propagation environment	Urban
Minimum equivalent field strength at reception place (dB(μV/m))	47 [i.25]
Path loss model	Recommendation ITU-R P.1546-4 [i.6]

Table B.3: Parameters of LTE system

	BS	UE
Simulation type	Snapshot	
Bandwidth(MHz)	5	
Cell type	Three sectors of single base station	
Coverage radius(m)	Urban:250, [i.27]	
Number of users per cell	5	
Distribution of users	random	
Snapshot number	(≥ 1 000)	
Parameters of transmitter/Receiver		
Down-tilt of transmitter Antenna	8°	
Gain of antenna (dBi)	15	0
Feeder loss of antenna(dBi)	1	0
Maximum transmitted power(dBm)	43	23
Minimum transmitted power(dBm)	-	-40
Noise figure(dB)	5	9
Propagation environment		
Path loss model	ITU-R P.1546-4 [i.6]	ITU-R P.1546-4 [i.6]
Standard deviation of log-normal fading (dB)	Urban 8	
Shadowing correlation factor	Inter BS 0,5; Inter cell 1	
Penetration loss (dB)	0	
MCL (dB)	MS-BS 70	
Propagation environment	urban	
Height of antenna(m)	35	1,5
Average terrain height(m)	Urban 20	
Power control	Off	PC Set1: 1/115
Link interface	TS 136 942 [i.27]	

Table B.4 shows the isolation distance based on Monte Carlo system simulation when the uplink data throughput loss is less than 5 %. Given the simulation parameters described above, for the adjacent channel configuration, the LTE-CR system should be located beyond 14 km isolation distance with the base station of DTMB coexist with the DTMB system. For the second adjacent channel configuration, the isolation distance is at least 10 km.

Table B.4: DTMB interfering TD-LTE-CR BS when the throughput loss of CR is less than 5 %

Scenario	Enviroment	ACIR(dB)	Isolation Distance(km)
Adjacent channel	urban	49,9	14
Second adjacent channel	urban	54,3	10

The relation between the isolation distance and the tolerable uplink data throughput loss of the TDD-LTE system are depicted in figures B.6 and B.7 for varying values of the allowed throughput loss.

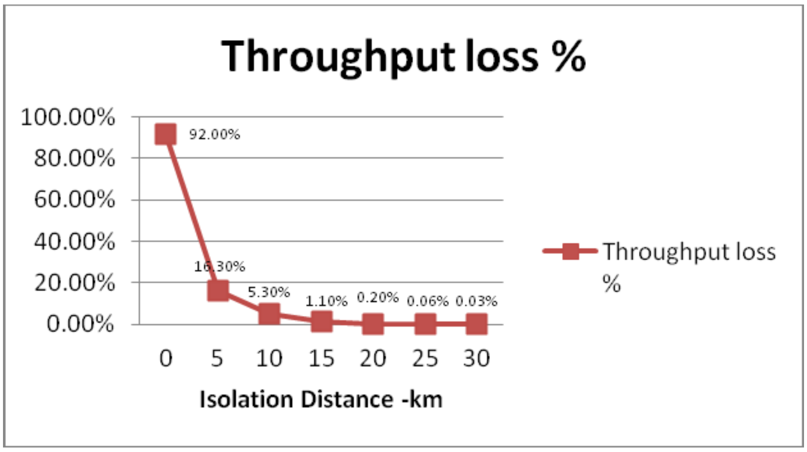


Figure B.6: Uplink data throughput VS isolation distance in adjacent channel scenario

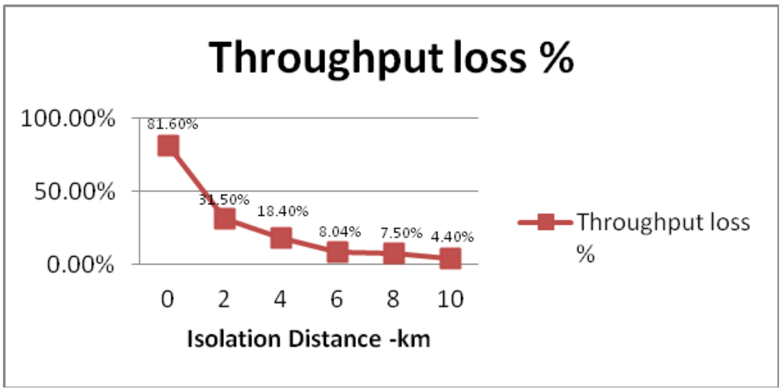


Figure B.7: Uplink data throughput VS isolation distance in second adjacent channel scenario

When the tolerable throughput loss is increased, the isolation distance requirement will be relaxed. Taking the adjacent channel configuration as an example, 1,1 % throughput loss is shown at 15 km isolation distance, and 16,30 % throughput loss is shown at 5km isolation distance. That means that when the tolerable throughput loss is increased, more available area can be exploited by LTE-CR system.

B.3 Coexistence conclusion

Based on the simulation assumptions and results above, if the LTE-CR system can tolerate a greater performance loss, it may be deployed to operate in TVWS closer to DTMB system which is operating in an adjacent and/or second adjacent channels. Meanwhile, robust interference avoiding technology incorporated into the LTE protocol and advanced hardware in CR systems may allow for more white space to be exploited by LTE-CR systems.

History

Document history		
V1.1.1	May 2013	Publication