Overview

• Update on latest White Space activities in US and UK
  – Adoption of White Space rules in US
  – Consultation released by Ofcom.

• Cognitive radio for the TV bands: challenges and solutions.

• Wireless Regional Area Networks (WRAN)
  – IEEE 802.22 Standard

• Personal/Portable Applications
  – Cognea and Ecma standardization

• Philips prototypes:
  – Sensing prototype
  – UHF Cognitive Radio prototype

• Conclusions
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• Conclusions

History

“‘The proposed reallocation of spectrum met with considerable political opposition. The television broadcasters did not want any spectrum to be taken away.’”

- 1968
PHILIPS

TV White Spaces Regulatory Milestones – US

- Notice of Inquiry
- Notice of Proposed Rule Making
- Public Notice
- Notice of Proposed Rule Making
- Initial R & O and Further NPRM
- Report on Sensing, Interference to DTVs & Other Radios
- Sensing Proto Testing
- Philips Complete CR Demo @ FCC
- Field Tests
- Final Rule and Order
- Cognea Alliance is Announced
- Final rules in Federal Registry
- First Cognea products
- Report on Interference Rej. Cap. of DTV Rx’s
- Cognea spec. transferred to ECMA for further development
- Final rules in Federal Registry
- Initial R & O and Further NPRM

PHILIPS

TV Band Incumbents

- Digital Television (DTV), Analog television (NTSC)
  - After the transition to DTV on June 12, 2009, some low-power NTSC stations will still remain and will need to be protected.
- Wireless microphones:
  - Currently are treated as secondary users of the TV spectrum.
  - Will be primary as far as unlicensed white space devices are concerned.
TV Sensing Problem: Hidden nodes

Path 1: signal from DTT transmitter goes direct to house aerial

Path 2: signal to mobile cognitive device blocked by tall building

Path 3: signal from mobile cognitive device to house aerial

Source: Ofcom Consultation
Feb. 16 2009

Wireless Microphone Sensing Problem

Wmic Tx

Wmic Rx

WSD

Desired Signal (-67 dBm)

Sensed Signal (-114 dBm)

Undesired Signal (-107 dBm)
FCC 2nd Report and Order (FCC 08-260, 11-14-2008)

• Both fixed and personal/portable devices allowed to operate in the TV white spaces on an unlicensed basis.

• All devices, except personal/portable devices operating in client mode, must include a geolocation capability and provisions to access over the Internet a database, established and administered by a third party.

• All devices must also have a capability to sense TV broadcasting and wireless microphone signals as a further means to minimize potential interference.

• Devices using sensing only as the protection mechanism may be allowed in the future, subject to additional FCC tests.

FCC 2nd Report and Order cont'

• Fixed Devices (e.g IEEE 802.22)
  – Up to 4 Watts EIRP.
  – Any channel between 2 and 51, except channels 3, 4 and 37.
  – Employ geo-location database and spectrum sensing to determine when TV channels are available.
  – Incorporate a dynamic frequency selection (DFS) mechanism to ensure that TV band devices operate only on vacant TV channels.
  – Shall employ a transmission power control (TPC) mechanism.
  – Not allowed in adjacent channel.
• Personal/Portable Devices
  – Up to 100mW; limited to 40mW if operating in adjacent channels.
  – Any channel between 21 and 51, except channel 37.
  – Mode II device (Master device) must employ geo-location database to determine channel availability.
  – Mode I device (Client device) operates under signaling control of Mode II device.
  – Employ sensing mechanism to determine channel availability in addition to geolocation.
  – Incorporate a dynamic frequency selection (DFS) mechanism and transmission power control (TPC) mechanism.
  – Future sensing only device operates <= 50mW.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Availability Check Time</td>
<td>30 sec</td>
</tr>
<tr>
<td>In-Service Monitoring Interval</td>
<td>60 sec</td>
</tr>
<tr>
<td>Channel Move Time</td>
<td>2 sec</td>
</tr>
<tr>
<td>Detection Threshold</td>
<td>ATSC: -114 dBm over 6 MHz</td>
</tr>
<tr>
<td></td>
<td>NTSC: -114 dBm over 100 kHz</td>
</tr>
<tr>
<td></td>
<td>WM: -114 dBm over 200 kHz</td>
</tr>
</tbody>
</table>
### Ofcom: UHF Band After Digital Switch Over in UK

<table>
<thead>
<tr>
<th>Channel (MHz)</th>
<th>Frequency (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21-32</td>
<td>470-478</td>
</tr>
<tr>
<td>33-44</td>
<td>574-661</td>
</tr>
<tr>
<td>45-56</td>
<td>741-765</td>
</tr>
<tr>
<td>57-68</td>
<td>766-798</td>
</tr>
</tbody>
</table>

- **Retained/interleaved spectrum**
- **Cleared spectrum**
- **PMSE**

Source: Ofcom Consultation Feb. 16 2009

### Ofcom on TV White Space

- Released consultation on White Spaces on Feb. 16 2009, with comments due by May 01 2009. Awaiting next statement.
- Proposed parameters:

<table>
<thead>
<tr>
<th>Cognitive parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity assuming a 0 dBi antenna</td>
<td>-114 dBm in 8 MHz channel (DTT)</td>
</tr>
<tr>
<td>Transmit power</td>
<td>-126 dBm in 200 kHz channel (wireless microphones)</td>
</tr>
<tr>
<td>Transmit-power control</td>
<td>13 dBm (adjacent channels) to 20 dBm</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>Required</td>
</tr>
<tr>
<td>Out-of-band performance</td>
<td>-44 dBm</td>
</tr>
<tr>
<td>Time between sensing</td>
<td>&lt; 1 second</td>
</tr>
<tr>
<td>Maximum continuous transmission</td>
<td>400 milliseconds</td>
</tr>
<tr>
<td>Minimum pause after transmission</td>
<td>100 milliseconds</td>
</tr>
</tbody>
</table>

Source: Ofcom Consultation Feb. 16 2009
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  - UHF Cognitive Radio prototype

Conclusions

Characteristics of cognitive/agile radios

Cognitive/agile radio = flexible re-configurable radio

("quickly adapts transmission characteristics")

+ smart

("aware of spectrum usage in vicinity, makes intelligent decisions on that basis, and reacts to evolving spectrum usage policies")
Cognitive Radio For the TV Band: Challenges

• Agile radios must detect primaries/incumbents, and at a much lower threshold
  – Primaries in UHF band: Analog and digital TV, Wireless microphones
  – Detection levels: -114 dBm
    • 1000 times lower than the minimum signal strength required to view TV
  – Incumbents like wireless microphones can appear and disappear any time
    • Periodic sensing required

• Long integration times needed for reliable detection at these levels
  – Sensing for this long means poor QoS support
    • Difficult to support VoIP

• Sensing Requirements
  – Fast, robust, coordinated sensing and quite periods, that protect incumbents as well as provide QoS.

ATSC signal characteristics

• Pilot
  – ATSC signal uses a 8-VSB (Vestigial Side Band) modulation with signal levels (-7,-5,-3,-1,1,3,5,7) + pilot value 1.25.
• Cyclostationarity
  – The ATSC signal is a digital signal with a symbol rate of 10.76 MHz.
PHILIPS

ATSC signal characteristics (cont’)

• PN 511 sequence
  – A 511-symbol long PN sequence is inserted in data stream every 24.2 ms.
• Segment-synch
  – The ATSC data is sent in segments of 828 symbols. At the beginning of each segment a 4-symbol sequence (5,-5,-5,5) is sent.
• Duty cycle
  – Last for hours

Wireless Microphone Signal Characteristics

• Part 74 compliant.
• 200 kHz bandwidth, 250 mW maximum transmit power in UHF.
  – 10 mW is more commonly used as the transmit power level.
• Center frequencies are 25 kHz apart, anywhere in the 6 MHz band including band-edges.
• No standard: most are FM, but newer ones are digital.
• Duty cycle: intermittent.
Philips sensing approach: Pilot-based sensing

- The ATSC pilot is a unique feature that can be used to sense the presence of the ATSC signal.

- Standard approach:
  - Narrow-band filter (~10 kHz) centered around nominal ATSC pilot location.
  - Calculate energy of filtered signal, compare to a threshold.

- Problems:
  - Pilot could be in a deep fade: quite common.
  - Threshold is susceptible to noise uncertainty.
  - Uncertainty in pilot location: could require a 100kHz bandwidth filter. The larger the filter bandwidth, the worse the performance.

- Challenge: Can ATSC pilot detection be made to provide robust sensing at SNR = -20 dB and short sensing times?

Spectrum Sensing: Solution

- Proposed solution:
  - Use a pilot based DTV sensing algorithm
  - Use a two stage sensing approach: Fast sensing, and, Fine sensing

## Cognitive Protocols

- Coordination of quiet periods between otherwise un-coordinated networks
- Channel management
  - Bootstrap, neighbor discovery
  - Channels appear and disappear
    - upon detection of incumbent vacate to pre-agreed backup channel
- QoS support with sensing and channel management
  - Schedule quiet periods for detection of incumbents

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- **Wireless Regional Area Networks (WRAN)**
  - IEEE 802.22 Standard
- Personal/Portable Applications
  - Cognea and Ecma standardization
- Philips prototypes:
  - Sensing prototype
  - UHF Cognitive Radio prototype
- Conclusions
IEEE 802.22 overview

- IEEE 802.22 is the cognitive radio based standard for the following:
  - Fixed point-to-multipoint wireless regional area networks
  - Reuse of TV broadcast bands on a non-interfering basis
  - PHY/MAC air interface specification

- Draft standard is under development
  - Expected to become an official IEEE standard in 2009

- Key design objectives
  - Primary protection (e.g., DTV, wireless microphones)
  - Secondary coexistence

Typical application of the 802.22 WRAN standard

- Wireless Regional Area Networks (WRANs)
  - Wireless broadband access (e.g. Rural areas)

- Topology:
  - Point-to-Multipoint
  - Master/Slave relationship

- Entities:
  - Base Station (BS)
  - Consumer Premise Equipment (CPE)
WRAN standard relative to other wireless network standards

- User net-peak-throughput
  - 18.72 Mbit/s

- Service Range:
  - 17-30 km depending on EIRP, up to 100 km

IEEE 802.22 System Architecture
IEEE 802.22 system parameters (draft specification)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency range</td>
<td>54~862 MHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>6 and/or 7, and/or 8 MHz</td>
</tr>
<tr>
<td>Data rate</td>
<td>1.51~22.69 Mb/s</td>
</tr>
<tr>
<td>Spectral Efficiency</td>
<td>0.25~3.78 b/s/Hz</td>
</tr>
<tr>
<td>Payload modulation</td>
<td>QPSK, 16-QAM, 64-QAM</td>
</tr>
<tr>
<td>Transmit EIRP</td>
<td>Default 4W for CPEs</td>
</tr>
<tr>
<td>Multiple Access</td>
<td>OFDMA/TDMA</td>
</tr>
<tr>
<td>FFT Mode</td>
<td>2048</td>
</tr>
<tr>
<td>Cyclic Prefix Modes</td>
<td>¼, 1/8, 1/16, 1/32</td>
</tr>
<tr>
<td>Duplex</td>
<td>TDD</td>
</tr>
</tbody>
</table>

IEEE 802.22: PHY Overview (draft specification)

- Modulation
  - OFDMA both in uplink and downlink
  - QPSK, 16-QAM, and 64-QAM

- TDD Duplexing

- Enhanced PHY features:
  - Adaptive sub-carrier allocation
  - Adaptive pilot insertion
  - Enhanced channel coding (LDPC, Turbo Code, SBTC)
IEEE 802.22: MAC overview (draft specification)

- Access mechanism: TDMA
  - Frame structure and QoS model similar to 802.16
- A new superframe structure defined:
  - Better coexistence and self-coexistence, synchronization, Part 74 beacon support, etc.
- Coexistence mechanisms:
  - Two-stage intra- and inter-frame mechanism and opportunistic sensing
  - Incumbent avoidance and Spectrum measurements (incumbents and itself)
  - Channel classification and Management
  - Dynamic resource sharing, Coexistence Beacon Protocol (CBP), Etiquette
  - Synchronization of overlapping BSs and quiet periods
  - Wireless microphone beacon mechanism (TG1)

---

IEEE 802.22 Superframe Structure

Superframe duration : 160 ms
Frame duration: 10 ms
Incumbents and Spectrum Sensing in 802.22

- Incumbents in TV bands
  - TV broadcasting services (in the US, use 6 MHz channels in VHF and UHF bands)
  - Wireless microphones (in the US, regulated by Part 74 FCC rules, use 50 mW for a 100 m coverage and 200 KHz channel bandwidth)
- Spectrum sensing requires
  - Sensing algorithms to quickly and robustly detect the presence of incumbent signals
  - Well-designed coordination and communication protocols
IEEE 802.22 spectrum sensing requirements

- Key incumbent sensing requirements defined within the IEEE 802.22 standard (draft)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value for Wireless Microphones</th>
<th>Value for TV Broadcasting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Detection Time</td>
<td>≤ 2 sec</td>
<td>≤ 2 sec</td>
</tr>
<tr>
<td>Channel Move Time</td>
<td>≤ 2 sec</td>
<td>≤ 2 sec</td>
</tr>
<tr>
<td>Channel Closing Transmission Time</td>
<td>100 msec</td>
<td>100 msec</td>
</tr>
<tr>
<td>Incumbent Detection Threshold</td>
<td>-107 dBm (over 200KHz)</td>
<td>-116 dBm (over 6MHz)</td>
</tr>
<tr>
<td>Probability of Detection</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>Probability of False Alarm</td>
<td>10%</td>
<td>10%</td>
</tr>
</tbody>
</table>

Reference: 802.22 FRD

Spectrum Sensing: Key Challenges

- Problem context:
  - Incumbents must be reliably detected within the CDT
    - 802.22 Draft Standard specifies IDT of -116 dBm and CDT of 2 sec
  - Reliable sensing requires network wide quiet periods (QP)
  - For typical energy detection approach, integration time is low, however, neighboring WRANs may be detected as incumbent
    - Higher probability of false alarms
  - Feature detection can accomplish more accurate detection of incumbents, however, the integration time required is the main issue
    - Long integration times mean poor QoS support, especially for VoIP

- Problem statement:
  - How to meet incumbent sensing requirements and support QoS?
**Sensing architecture and strategy**

- **Begin Sensing**
- **Fast Sensing** (Analog, RSSI, MRSS, FFT...)
  - **MAC** (Select single channel)
  - **Spectrum Usage Database (BS)**
- **Fine/Feature Sensing**
  - **MAC**
  - **End Sensing**

**Fine sensing algorithms***

- **FFT-based pilot detection**
  - Pilot-energy detection: find maximum of FFT output-squared, and compare to a threshold
  - Pilot-location detection: compare location of maximum of FFT-output between multiple dwells

- **Spectrum sensing of the DTV in the vicinity of the pilot using higher order statistics**
  - Detect the DTV signals in Gaussian noise using higher order statistics (HOS)
  - Perform non-Gaussianity check in the frequency domain in the vicinity of the pilot of the DTV

---

*Note: These two sensing algorithms have been approved by IEEE 802.22 for fine sensing as informative purpose. More sensing algorithms have been submitted for discussion and are described in the 802.22 draft.*
Performance of FFT-based pilot detection

Note: 12 signals supplied by MSTV to IEEE 802.22 for testing different sensing algorithms

Performance of FFT-based pilot detection w/ 2 dB average noise uncertainty
Spectrum sensing of the DTV in the vicinity of the pilot using higher order statistics

Reference: Apurva Mody, BAE Systems, August 2007, doc.: IEEE 802.22-07/0370r2

Performance of DTV sensing in the vicinity of the pilot using higher order statistics

\[ \gamma = 0.8, P_D > 0.9 \text{ and } P_{FA} < 0.05 \]

\[ \gamma = 1.05, P_D > 0.9 \text{ and } P_{FA} = 0.01 \]

Reference: Apurva Mody, BAE Systems, August 2007, doc.: IEEE 802.22-07/0359r1
Sensing schedule on the MAC layer

- Spectrum Sensing is performed during network quiet periods (QPs) scheduled by the BS
- Two types of QPs for sensing:
  - Intra-frame (Fast sensing)
  - Inter-frame (Fine sensing)

Synchronization of QPs among neighboring WRANs

- QPs of neighboring WRANs should be synchronized for more reliable sensing
  - especially for in-band sensing in the operating channel (N) and adjacent channels (N+/-1)
Coexistence Beacon Protocol (CBP)

- CBP packets carry the schedule of the QPs and self-coexistence information
- Three cases

Case 1:

Case 2:

Case 3:

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**TC48-TG1 - TV White Spaces**

**Scope:**
Wireless communications using Television White Spaces (TVWS).

**Programme of work:**
1. To develop and maintain Standards and Technical Reports for TVWS wireless communication systems, including:
   - Physical Layer (8P and Raiddband);
   - MAC layer (Media Access Control);
   - Protocol and mechanisms for coexistence.
2. To cooperate and liaise with other organizations and standardization bodies.

**Convenor**
Dr. Kyutae Lim (GEDEC)

**Secretary**
Mr. O. Eltinga (Ecma)
Cognea: Whole home application

- Television white spaces will enable wireless distribution of high-quality high-definition television for whole home, vastly improving the DTV experience.
- The new standard will provide reliable and robust coverage anywhere in a home, while consuming much lower power.

Cognea: Community internet access application

- Television white spaces will provide more widely available and cost effective access to the internet in underserved markets.
- The superior propagation characteristics provide much greater coverage range than existing unlicensed technologies.
Ecma TC48-TG1 Standardization: General technical spec. and functions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating frequency</td>
<td>• CH21<del>51 (512</del>698MHz) except CH37(608~614MHz)</td>
<td>FCC 08-260</td>
</tr>
<tr>
<td>Channel bandwidth</td>
<td>• 6, 7, 8MHz</td>
<td></td>
</tr>
<tr>
<td>Channel bonding and</td>
<td>• Optional</td>
<td>Not in 1st edition</td>
</tr>
<tr>
<td>aggregation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data rate</td>
<td>• Upto 20 Mbps at 55 m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Upto 3 Mbps at x100 m</td>
<td></td>
</tr>
<tr>
<td>Multiple antenna</td>
<td>• Optional</td>
<td></td>
</tr>
<tr>
<td>Mesh architecture</td>
<td>• Optional</td>
<td></td>
</tr>
<tr>
<td>Medium access</td>
<td>• Reservation-based access</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Contention-based access (yielding to reservation)</td>
<td></td>
</tr>
<tr>
<td>Link layer protection</td>
<td>• Supported</td>
<td></td>
</tr>
<tr>
<td>Network security</td>
<td>• Supported</td>
<td></td>
</tr>
<tr>
<td>QoS</td>
<td>• Support delay-bounded packet and bandwidth</td>
<td>reservation</td>
</tr>
<tr>
<td></td>
<td>reservation</td>
<td></td>
</tr>
</tbody>
</table>

Ecma TC48-TG1 Standardization cont’

- PHY features
  - OFDM based system
    - 128 FFT
  - Multiple PHY data rates to support different applications and QoS requirements
    - Supports full HD streaming using one TV channel
  - Inner and outer coding
    - Convolutional code and RS code
    - Puncturing of a base inner code to provide multiple code rates
  - Normal and burst modes to support different application types
  - Low preamble overhead
  - Hopping pilot pattern
    - Repeats every six symbols
  - Enhanced retransmission scheme
Ecma TC48-TG1 Standardization cont’

• MAC features
  – MAC architecture
    • Infrastructure mode: master-slave
    • Ad hoc mode: peer-peer
  – Channel access and frame processing
    • Support both reservation based access and contention based access
    • Highly optimized QoS and efficient support for HDTV
  – Incumbent protection
    • DFS and TPC based on geo-location/database and sensing
  – Self-coexistence between networks
    • Use beacon exchange for coordination
  – Security
    • Supported

Ecma TC48-TG1 Standardization cont’

• Protocol reference model

![Diagram of protocol reference model]
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Philips Sensing Prototype

• The prototype consists of
  – a Philips TV tuner
    • for tuning to a specified 6 MHz TV channel and translating to IF frequency of 44 MHz
  – a digital processing board
    • for A/D and processing, and,
  – a computer
    • for user-interface, control and processing.
Philips Sensing Prototype at FCC OET

Prototype User Interface (UI)

FCC Report, October 2008: Clean Signal

Philips Prototype WSD Detection Sensitivity to Clean DTV Signal
FCC Report, October 2008: Captured Signals

Philips Prototype WSD Detection Sensitivity to RF Captures

- A CR network for UHF bands
  - with real-time sensing operating in TV bands,
  - WiFi-like MAC extended to show distributed and cognitive features, and,
  - OFDM PHY (5 MHz wide)
  - Frequency translator

Philips WS Prototype: UHF Cognitive Radio Architecture

- MAC: WiFi-like MAC extended to include ad-hoc distributed architecture and cognitive features
- PHY: OFDM (WiFi-like), 5 MHz wide
- Frequency Translator: From 5 GHz to UHF bands and vice versa
- Sensing: Real-time FPGA implementation, operating directly in UHF bands
Block Diagram of UHF Cognitive Radio Node

UHF COGNITIVE RADIO NODE

Philips UHF Prototype
Philips UHF Demo Set Up

- Demonstrates all aspects of CR
  - Incumbent sensing on boot-up and during quiet periods
  - Cognitive MAC protocols to detect incumbents and handle channel switching

- The CR nodes identify home channel and backup channel and exchange this information with each other

- The video is transmitted on a vacant UHF TV channel
  - Switches to a backup channel when an incumbent is detected on home channel
**Demo: Monitoring of UHF TV bands**

- Continuously scans the UHF channels 21-51 for
  - ATSC and NTSC
  - Wireless microphone
  - Secondary transmissions

- Very short sensing time enables faster detection of incumbents
  - Minimizes interference to incumbents
  - QoS is maintained.

**Conclusions**

- With the recent FCC ruling, the stage is set for cognitive devices in the TV white spaces.
- The technology for the various parts: sensing, geolocation/database, dynamic frequency selection, have been demonstrated by various companies.
- Industry standards need to be developed quickly to maximize the use of this spectrum.