Towards White Space Use: What Does CREW Bring To The Table?

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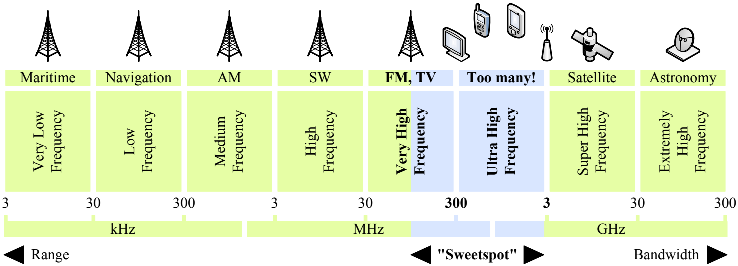
CTVR the telecommunications research centre

The Radio Frequency Spectrum



Source: J. P. Miranda, "Multi-standard Context-aware Cognitive Radio: Sensing and Classification Mechanisms", Ph.D. Defense, Dec. 2012

- Vital resource for a number of applications and services
- Useful portions set by the tradeoff range *vs.* bandwidth
- "Sweetspot" spans from the upper VHF to the UHF bands

The Radio Frequency Spectrum

Sweetspot: Current Usage

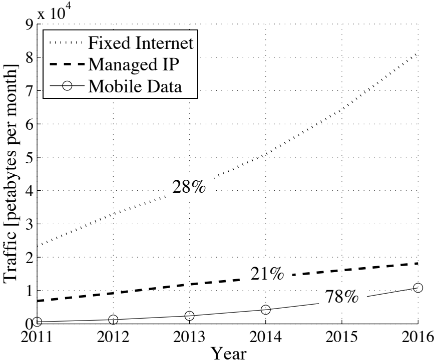
- Observed utilization levels range from 15% to 85%
- Up to 56% of the TV channels in Europe are unused
- 2.4 GHz band used only 40% in the busiest locations
- 5 GHz band are almost completely unutilised

White Spaces

Spectral resources that are assigned and allocated, but not being used at a particular time in a particular geographic area

Demand Forecast for 2011-2016

Global IP Traffic

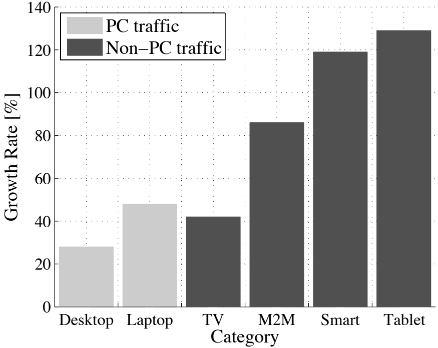


- Mobile data has the highest growth rate (78%)
- Wi-Fi and mobile devices will account for 61% in 2016 (from only 45% in 2011)

Source: J. P. Miranda, "Multi-standard Context-aware Cognitive Radio: Sensing and Classification Mechanisms", Ph.D. Defense, Dec. 2012

Demand Forecast for 2011-2016

Consumer Internet Traffic



- Mobile data has the highest growth rate (78%)
- Wi-Fi and mobile devices will account for 61% in 2016 (from only 45% in 2011)
- Twofold increase in mobile data traffic offload

Source: J. P. Miranda, "Multi-standard Context-aware Cognitive Radio: Sensing and Classification Mechanisms", Ph.D. Defense, Dec. 2012

Problem Statement

How can we accommodate this increasing traffic demand while at the same time improving spectrum efficiency?

- Policy
- Technology
- Regulation
- Standardization

Outline

Part I: Policy, Technology, and Coexistence Methods

Part II: Recent Advances in Regulation & Standardization

Part III: Experimentally-driven Research: CREW Achievements

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Part I: Policy, Technology, and Coexistence Methods

Part II: Recent Advances in Regulation & Standardization

Part III: Experimentally-driven Research: CREW Achievements

Policy

Dynamic Spectrum Access

- Introduces flexibility into current management policies
- Leverages deployment of innovative reconfigurable systems
- Operating frequencies are selected dynamically
- Data can be conveyed opportunistically over white spaces

Overlay Access Model

Lower priority unlicensed systems are allowed to share spectrum with higher priority licensed systems provided that the former can determine white spaces prior to transmission

Technology

Software-defined Radio

- Software components
- Processing in software
- Parameter reconfiguration
- Run-time changes possible

Cognitive Radio

- Provides wireless devices with context-awareness
- Goal-driven autonomous configuration

White Space Devices

Able to operate opportunistically, possibly on an unlicensed basis, wherever underutilized spectrum exists

Coexistence Methods

Some prominent candidates relevant to CREW:

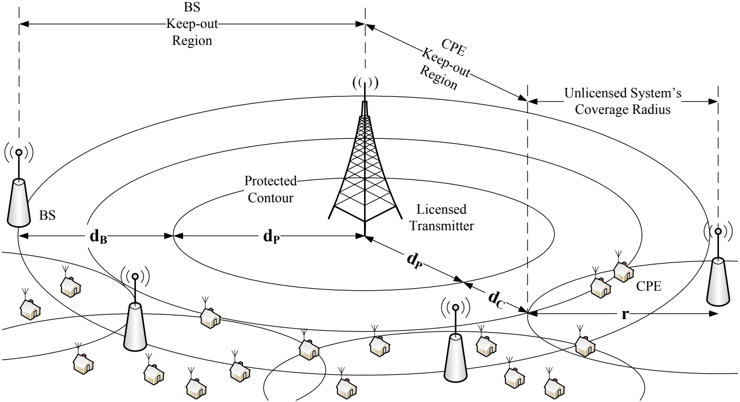
1. Geo-location/Database Access
2. Spectrum Sensing
3. Cyclostationary Signatures

1. Geo-location/Database Access

Working Principle

- Allows WSD to obtain a list of permitted channels before initiating operation and without sensing the spectrum
- Uses a RF propagation model to estimate the electromagnetic field strength received at a certain geographical location
- Populates a database with services granted protection, their locations, protection requirements, and operation channels
- Frequency selection is carried out on the basis of information on available frequencies associated with locations in the database and location information received from WSD

1. Geo-location/Database Access



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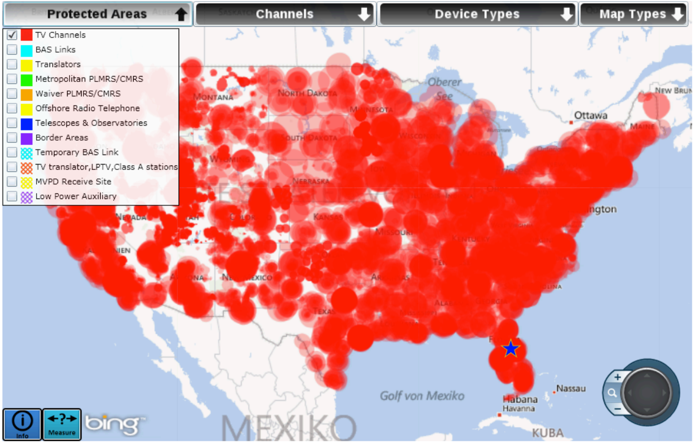
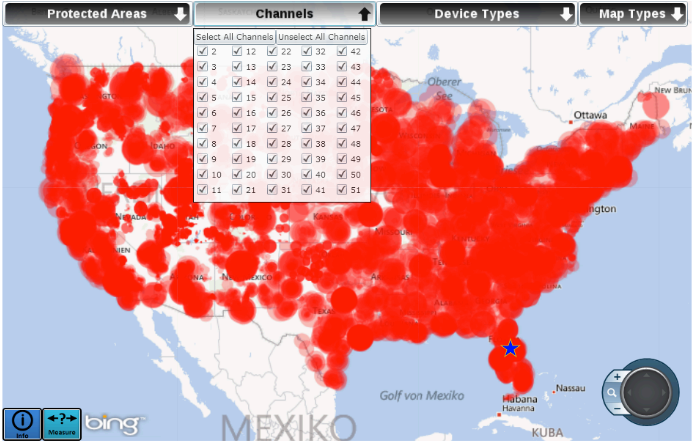


Source: http://whitespaces.spectrumbridge.com

1. Geo-location/Database Access



Source: http://whitespaces.spectrumbridge.com

1. Geo-location/Database Access

Nevada County, California

HAAT: 79.30 meters

Channel Number	Frequency Range (MHz)	Allowable Antenna HAAT (meters)	Noise Floor (dBm)
2	54-60	250	**
5	76-82	250	**
6	82-88	150	**
10	192-198	10	**
11	198-204	250	**
14	470-476	250	**
15	476-482	10	**
16	482-488	250	**
17	488-494	250	**
18	494-500	200	**
19	500-506	250	**
20	506-512	250	**
21	512-518	30	**
22	518-524	250	**
23	524-530	30	**
24	530-536	250	**
28	554-560	200	**
29	560-566	250	**
30	566-572	250	**
31	572-578	250	**
32	578-584	250	**
33	584-590	250	**
34	590-596	250	**
35	596-602	30	**
39	620-626	250	**
40	626-632	30	**
41	632-638	250	**
42	638-644	10	**
46	662-668	30	**
47	668-674	150	**
48	674-680	75	**
49	680-686	250	**
50	686-692	10	**
51	692-698	250	**

http://whitespaces.spectrumbridge.com

Channel Number	Frequency Range (MHz)	Allowable TX Power (mW)	Noise Floor (dBm)
21	512-518	100	**
22	518-524	100	**
23	524-530	100	**
24	530-536	100	**
25	536-542	40	**
27	548-554	40	**
28	554-560	100	**
29	560-566	100	**
30	566-572	100	**
31	572-578	100	**
32	578-584	100	**
33	584-590	100	**
34	590-596	100	**
35	596-602	100	**
39	620-626	100	**
40	626-632	100	**
41	632-638	100	**
42	638-644	100	**
43	644-650	40	**
45	656-662	40	**
46	662-668	100	**
47	668-674	100	**
48	674-680	100	**
49	680-686	100	**
50	686-692	100	**
51	692-698	100	**

Channel Number	Frequency Range (MHz)	Availability	Noise Floor (dBm)
36	602-608	Exclusive	**
38	614-620	Exclusive	**
9	186-192	Available	**
12	204-210	Available	**
2	54-60	White Space	**
5	76-82	White Space	**
6	82-88	White Space	**
10	192-198	White Space	**
11	198-204	White Space	**
14	470-476	White Space	**
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1. Geo-location/Database Access

Lower Manhattan, New York City

HAAT: 8.79 meters

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Channel Number	Frequency Range (MHz)	Allowable TX Power (mW)	Noise Floor (dBm)
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49	680-686	White Space	**

1. Geo-location/Database Access

Practical Issues

- Largely dependent on how accurately a WSD can determine its geographical position
- Required accuracy depends on the granularity used in the process of coverage modeling, *i.e.*, the size of the pixel representing a given geographical location
- Estimated frequencies may not reflect current availability:
  - Propagation models do not measure actual field strengths
  - WSD need to get instructed about changes in the database
  - Only services in the database are granted protection

1. Geo-location/Database Access

What does CREW bring to the table?

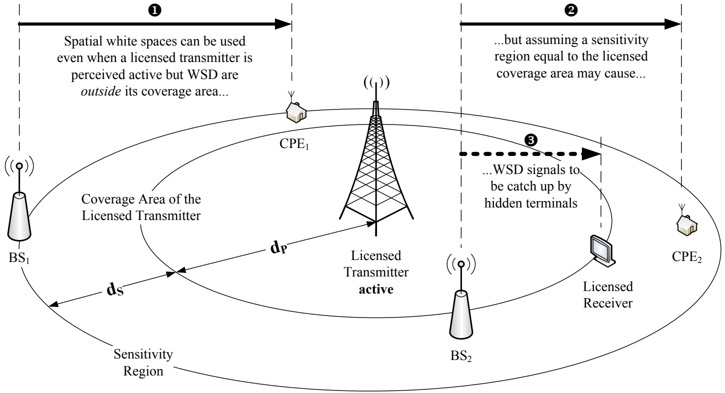
- Two experiments have been carried out in Y2 to assess the performance of this method in the TV bands:
  - Assisted by real measurements from a <u>standalone</u> sensor
  - Measurement campaign involving multiple sensors
- More to come in Y3:
  - Performance comparison: database *vs.* multiple sensors
  - Assisted by real measurements from a <u>sensor network</u>

2. Spectrum Sensing

Working Principle

- Estimates a specific parameter of the licensed signal (to be detected) using a test statistic
- Decides on the channel availability is made via statistical hypothesis testing, *e.g.*, by constructing a test statistic and comparing it to a detection threshold using some criterion
- Tailored to detect the presence of licensed signals over a pre-determined signal space

2. Spectrum Sensing



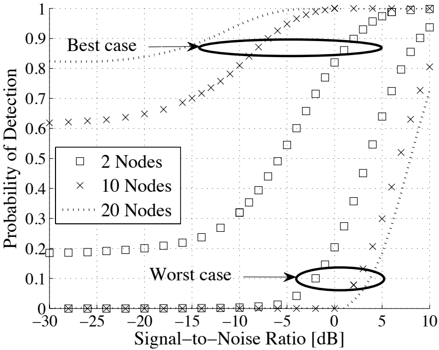
Source: J. P. Miranda, "Multi-standard Context-aware Cognitive Radio: Sensing and Classification Mechanisms", Ph.D. Thesis (To Appear)

2. Spectrum Sensing

Node Cooperation

- Uncertainties make it difficult for a standalone WSD to detect weak licensed signals
- If copies of a signal are received over multiple channels then the risk that all channels simultaneously experience shadowing or fading can be dramatically reduced
- Can significantly mitigate the hidden terminal problem by instructing multiple WSD (nodes) to scan the same channel
- Multiple nodes can alternatively “team up” to scan different channels, thus reducing detection delays

2. Spectrum Sensing



- Fading and shadowing can be mitigated by enforcing cooperation among nodes

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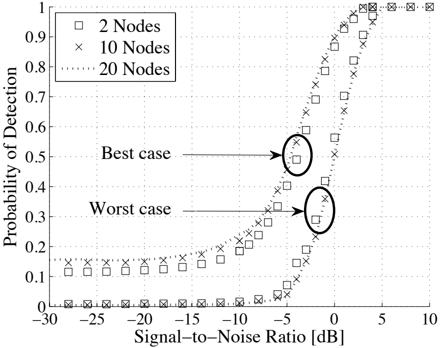

- Fading and shadowing can be mitigated by enforcing cooperation among nodes
- Some techniques deliver lower cooperation gains

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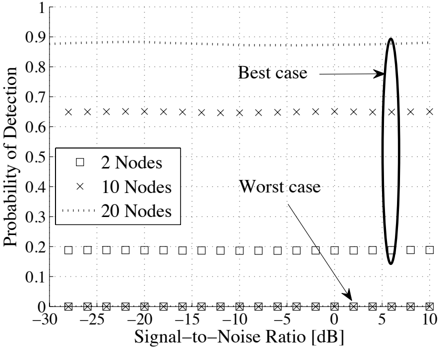
2. Spectrum Sensing



- Fading and shadowing can be mitigated by enforcing cooperation among nodes
- Some techniques deliver lower cooperation gains
- Some issues <u>cannot</u> be alleviated via cooperation

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2. Spectrum Sensing

Practical Issues

- Correlated shadowing hinders nodes physically close to one another from improving the global achievable performance
- Requires a bidirectional control channel over which control signals are broadcast (downlink) and local information is reported back (uplink)
- Cooperation gains are <u>limited</u> in practice if local information is conveyed over imperfect control channels
- Largely dependent on the signal processing technique used to collect channel samples at the local level

2. Spectrum Sensing

What does CREW bring to the table?

- Infrastructure:
  - Standards: DVB-T, 802.11, 802.15.1, 802.15.4, LTE
  - Hw1: Tmote Sky, eyesIFX, TelosB, Wi-Spy, USRP, BEE2
  - Hw2: Sensing agent, multi-antenna LTE detector
  - Sw & Reg: Iris SDR, Test & trial TV band licences
  - Initiative: http://whitespacesireland.wordpress.com
- Exemplary experiments:
  - Y1: Context-awareness in ISM bands (D6.1, wiNTECH'11)
  - Y3: Reduce complexity by using TV dongle + Raspberry Pi

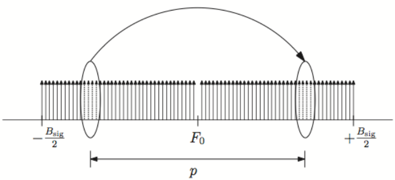
3. Cyclostationary Signatures

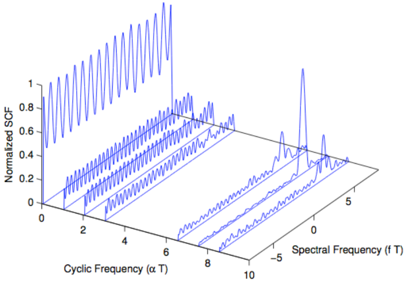
Working Principle

- Intentionally embedded in digital signals to facilitate signal detection/classification, frequency acquisition, network identification, and frequency rendezvous
- Best suitable when transceivers dynamically choose operation parameters and no predefined channelization scheme exists
- In contrast to inherent cyclostationary features, the features created by embedding signatures can be manipulated without impacting system performance

3. Cyclostationary Signatures

Signature Generation: Single (Feature) Signature

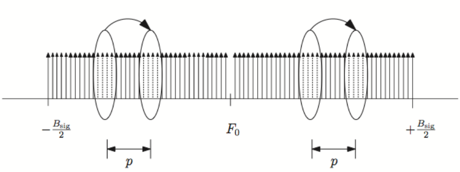


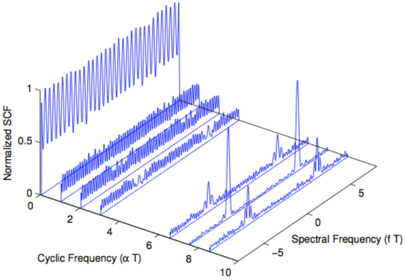


Source: P. D. Sutton, "Rendevouz and Coordination in OFDM-based DSA Networks", Ph.D. Thesis, Sept. 2008

3. Cyclostationary Signatures

Signature Generation: Double (Feature) Signature





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3. Cyclostationary Signatures

Practical Issues

- Designed to examine waveforms intended to be demodulated, so long observation time and small frequency resolution are required at very low SNR regimes
- Does not find application in the current scenario because both regulators and standards specify strict channelization schemes, *i.e.* no need for spectrum rendezvous
- Type of bootstrapping mechanism that will <u>become</u> important as soon as more flexible spectrum access is permitted

3. Cyclostationary Signatures

What does CREW bring to the table?

- One (demo) experiment has been carried out in Y2 to assess the feasibility of this method:
  - Facilitates spectrum rendezvous in the TV bands for the case that no channelization scheme exists
  - Allows to independent network coalitions (INC)
- More to come in Y3:
  - Seamless mobility between heterogeneous networks
  - No prior knowledge with respect to the channels used

Outline

Part I: Policy, Technology, and Coexistence Methods

Part II: Recent Advances in Regulation & Standardization

Part III: Experimentally-driven Research: CREW Achievements

Regulation

FCC Et. Docket 10-174 (Sept. 2010)

- Finalizes the rules to make unused spectrum in the TV bands available for unlicensed WSD
- Determines that WSD can use geo-location/database access as the sole means to identify white spaces
- Licensed users will be granted adequate protection by registering to the database and other provisions of the rules
- Defines requirements for sensing-only WSD but certification will occur under a rigorous proof-of-performance standard

Regulation

FCC Et. Docket 11-131 (Jan. 2011)

- Designates multiple database administrators for an initial period of 5 years
- Finds that having multiple parties developing business models for this new mechanism is in the public interest
- First public trials were concluded without any report of critical nature

Regulation

FCC GN Docket 12-354 (Dec. 2012)

- Proposes the creation of a new broadband service in the 3.5 GHz band, currently used for military and satellite operations
- Reflects recommendations previously made in:
  - The American National Broadband Plan (Mar. 2010)
  - The PCAST report (Jul. 2012)

Goal of this NPRM

Aim at enabling more efficient use of spectrum by promoting two major advances, namely small cells and spectrum sharing

Regulation

CEPT ECC Report 159 (Jan. 2011)

- Determines preliminary technical and operational requirements for WSD operation in the 470–790 MHz band
- Points out geo-location/database access as the most feasible method (compared to standalone sensing and beacons)

For Further Consideration

Address a number of technical and regulatory issues raised by the introduction of WSD into the market, in particular develop a regulatory framework for the operation of geo-location databases

Regulation

CEPT ECC Report 185 (Jan. 2013)

- Extends analysis on sensing with node cooperation and concludes that the latter can effectively alleviate local issues like fading and shadowing
- Extends analysis on coexistence to ARNS, TETRA TEDS, CDMA-PAMR, as well as cable head-ends
- Assesses the performance of TV broadcast and PMSE in the presence of interference from WSD and defines the maximum permitted power limits for the WSD operation

Regulation

CEPT ECC Report 186 (Jan. 2013)

- Defines general principles and operational requirements to the operation of WSDs under the master/slave concept
- Lists the areas of uncertainty that the database has to deal with, *i.e.* victim receiver, master WSD, and slave WSD
- Develops approaches for calculating in-block and out-of-block emission levels, as well as methods to deal with interference aggregation from multiple WSDs
- Recognises the combined use of geo-location and sensing

Standardization

New CR standards have been developed:

- ECMA-392 (Dec. 2009)
- IEEE 802.22 WRAN (Jul. 2011)
- IEEE 802.19 Coexistence Assurance (under development)
- IETF PAWS (under development)

Existing standards have been amended with CR capabilities:

- IEEE 802.15.2 WPAN (Aug. 2003)
- IEEE 802.16h WiMAX (Jul. 2010)
- IEEE 802.11af WLAN (under development)

Outline

Testbed implementation is tough but...

...may be rewarding in the following ways:

- Of practical interest because it allows us to visualize (and gain insight on) issues that cannot be captured by other means, *e.g.* analytically or by means of simulation
- Such real-world insights gained through experimentation can be feed back into the theory
- Has been proved successful in creating dialogue oportunities with regulators on related issues
- Provides more tangible results and as such constitutes a more suitable mechanism for attracting industry collaboration

Exemplary CREW Experiments

Geo-location/Database Access + Spectrum Sensing

1. Context-awareness in TV White Space (Y1)
2. Experimental Coexistence Study in TV Bands (Y3)

Cyclostationary Signatures

3. Receiver-driven Handover in Independent Networks (Y2)

1. Context-awareness in TV White Space

Motivation

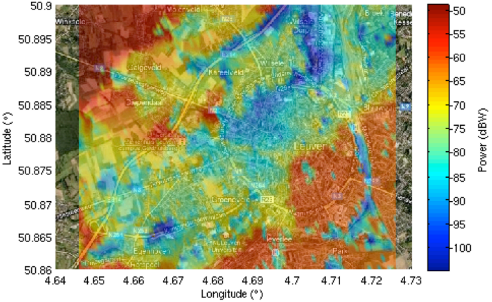
- The sole use of geo-location/database access leads to significant dependency on the RF propagation model used
- This makes it necessary to add large margins to the estimated protection contours so as to avoid interference to the licensed users granted protection by the database

Target of this Experiment

Can this difficulty be overcome by improving the estimates of the RF propagation model with actual (sensing) measurements?

1. Context-awareness in TV White Space

Geo-location/Database Access: Exemplary Power Map

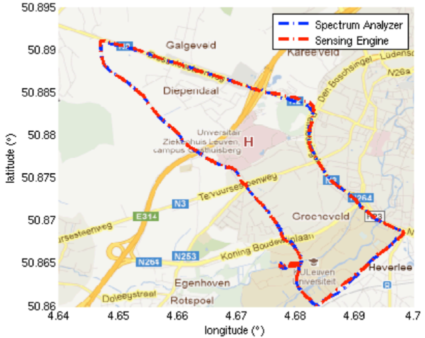


- DVB-T coverage predicted using Longley-Rice model with terrain information
- Channel 40, city of Leuven
- Accuracy impacted by unknown parameters, *e.g.* ϵ_r, σ, and climate

Source: CREW Deliverable D6.2, "Experimentation Results of a Second Set of Test Cases", Sept. 2012

1. Context-awareness in TV White Space

Spectrum Sensing: Field Measurement Campaign

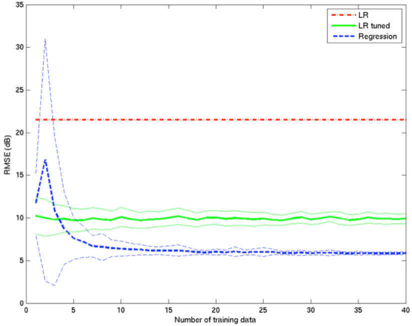


- Rohde & Schwarz spectrum analyzer and a homemade low-cost platform
- Done while riding a bike on a fixed route with laptop and GPS module in a backpack
- Two databases built based on the measurements

Source: CREW Deliverable D6.2, "Experimentation Results of a Second Set of Test Cases", Sept. 2012

1. Context-awareness in TV White Space

Combined Approach: Root Mean Squared Error

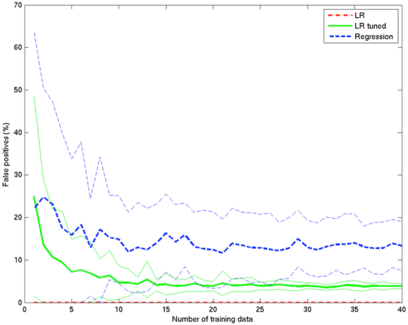


- Longley-Rice model can be tuned so as to minimize the RMSE of its estimates
- Linear regression drops RMSE from 21.5 to 10 dB
- Further reduction of 4 dB obtained with log regression

Source: CREW Deliverable D6.2, "Experimentation Results of a Second Set of Test Cases", Sept. 2012

1. Context-awareness in TV White Space

Combined Approach: False Positives and False Negatives



- Longley-Rice model grants highest level of protection for licensed users

Source: CREW Deliverable D6.2, "Experimentation Results of a Second Set of Test Cases", Sept. 2012

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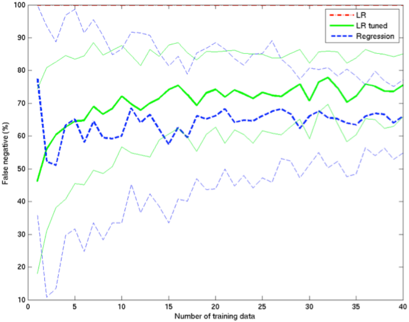
Combined Approach: False Positives and False Negatives



- Longley-Rice model grants highest level of protection for licensed users
- Tuned Longley-Rice and linear regression models outperform default model
- Better efficiency at the cost of lower protection

Source: CREW Deliverable D6.2, "Experimentation Results of a Second Set of Test Cases", Sept. 2012

2. Experimental Coexistence Study in TV Bands

Motivation

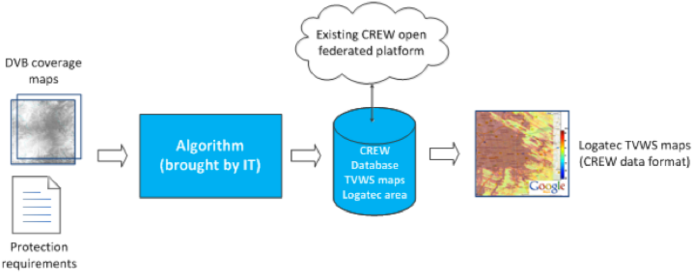
- Hybrid solutions that couple geo-location/database access with spectrum sensing have been increasingly recognized as able to make more efficient use of white spaces
- The practicality of such hybrid solutions has not been assessed in field trials yet, neither in the U.S. nor in Europe, when field measurements are provided by a sensor network

Target of this Experiment

What are the benefits of a solution where the database is assisted by a low-cost, densely deployed, distributed sensor network?

2. Experimental Coexistence Study in TV Bands

Step 1: Populate the database



- DVB-T field strength coverage wil be provided by APEK
- Power maps will be computed using an algorithm from IT

Source: CREW OC2 Proposal, "Experimental coexistence study in TV bands", Oct. 2012

2. Experimental Coexistence Study in TV Bands

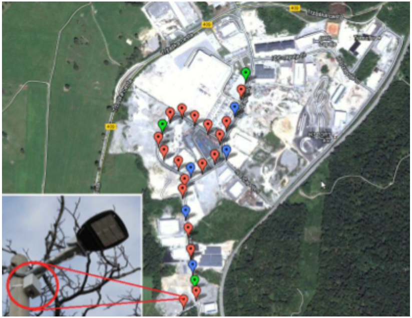
Step 2: Connect WSD with the database

- WSD will be based on Iris SDR, provided by TCD
- Communication protocol will be a draft version of PAWS

Source: CREW OC2 Proposal, "Experimental coexistence study in TV bands", Oct. 2012

2. Experimental Coexistence Study in TV Bands

Step 3: Connect sensors with the database



- Connect the sensor network @JSI with the database
- Protocol will allow periodic upload of information from the sensors to the database
- Protocol messages will be based on the existing CREW common data format

Source: CREW OC2 Proposal, "Experimental coexistence study in TV bands", Oct. 2012

3. Receiver-driven Handover in Independent Networks

Motivation

- Suppose that unlicensed white space use is made available on an opportunistic basis so new access providers come into play
- Deployed base stations will likely have different settings (no a priori channelization at the band) thus giving rise to several independent networks

Target of this Experiment

Are cyclostationary signatures a feasible means to allow spectrum rendezvous and thus enforce network coalitions in the TV bands?

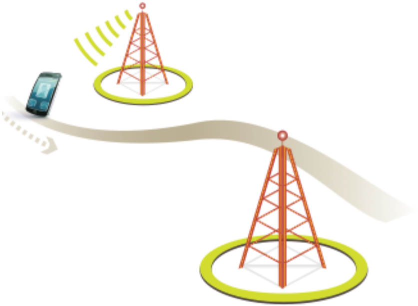
3. Receiver-driven Handover in Independent Networks

Storyline of the Demo

- Cyclostationary signatures are embedded in all transmissions on the network
- Upon forming a coalition, subnetworks embed a common cyclostationary signature in their transmissions
- A mobile user associated with a certain INC searches for transmissions containing the signature of its INC
- When this is found the mobile user performs a rendezvous and connects to those base stations

3. Receiver-driven Handover in Independent Networks

Handover Procedure: Step 1



- Terminal achieves rendezvous with INC member BS

Source: J. Tallon et al., "Receiver-driven Handover between Independent Networks", DySPAN, Oct. 2012

3. Receiver-driven Handover in Independent Networks

Handover Procedure: Step 2

- Terminal achieves rendezvous with INC member BS
- Rendezvous with a second member BS is followed by power comparison

Source: J. Tallon et al., "Receiver-driven Handover between Independent Networks", DySPAN, Oct. 2012

3. Receiver-driven Handover in Independent Networks

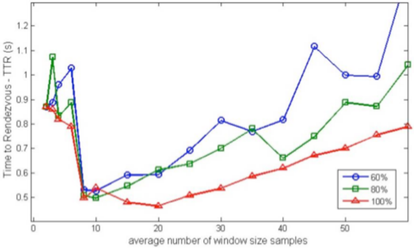
Handover Procedure: Step 3

- Terminal achieves rendezvous with INC member BS
- Rendezvous with a second member BS is followed by power comparison
- Terminal makes switch and begins to scan for new BS

Source: J. Tallon et al., "Receiver-driven Handover between Independent Networks", DySPAN, Oct. 2012

3. Receiver-driven Handover in Independent Networks

Time To Rendezvous vs. Number of Correlations



- TDD control channel so the receiver can reply to the BS on the same channel
- 10 correlations are sufficient to achieve good performance regardless of the duty cycle

- Time taken for rendezvous can be significantly reduced in many different ways, *e.g.* efficient coding or better hardware

Source: CREW Deliverable D6.2, "Experimentation Results of a Second Set of Test Cases", Sept. 2012

Conclusions

What does CREW bring to the table?

- Our federation of testbeds allows experimenters to remotely access and use an infrastructure that is unique in Europe
- Insightful experiments assessing the coexistence methods regarded as most promising by regulators and adopted (or currently under consideration) by a number of standards
- Consistent record of dissemination activity in conferences, workshops & tutorials, and open calls (D8.1 and D8.2) as well as in terms of regulation and standardization (D8.1 and D8.3)