COGEU is a Specific Target Research Project (STREP) supported by the 7th Framework Programme, Contract number: 248560
WHAT IS COGEU?
The **COGEU** project is a composite of

- technical,
- business, and
- regulatory/policy domains,

with the objective of taking advantage of the TV digital switch-over (or analog switch-off) by developing cognitive radio systems that leverage the favourable propagation characteristics of the TVWS through the introduction and promotion of real-time secondary spectrum trading and the creation of new spectrum commons regime.
In Europe the complete digital switch over is planned for 2012 and will open a “once in a lifetime” opportunity for the networks of the future.
In Europe the complete digital switch over is planned for 2012 and will open a “once in a lifetime” opportunity for the networks of the future.

By switching from analogue to digital transmission more television channels can be broadcast using less spectrum. After analogue switch off the spectrum 790 MHz to 862 MHz (ch. 61 to 69), the so called digital dividend, will be/was entirely cleared from broadcast.
Motivation

• Within the remaining spectrum (470 MHz to 790 MHz) not all channels are occupied at each location. **These locally unused channels are referred to as TV White Spaces (TVWS).**
• How do we transform the TV White Spaces into social benefits and economic growth?
Motivation
Motivation

- TVWS are quite stable because terrestrial broadcasting is planned around relatively inflexible ‘high power – high tower’ distribution networks.
- Strong interest by mobile cellular network operators to use lower frequencies, as network rollouts costs are dramatically lower.
COGEU domains

Regulation domain

Economic domain

Technology domain
COGEU consortium
AND AT THE END?
Final COGEU demo
TVWS database

Final COGEU demo
TVWS geo-location database
TVWS geo-location database
TVWS geo-location database
Final COGEU demo

policies
Final COGEU demo

assignment
Final COGEOU demo
TVWS transceiver

creating a node-to-node link in TVWS
COGEU TVWS Transceiver

Software-based Cognitive Radio: IRIS / Labview

RF-frontend for Interleaved TV spectrum

Baseband Signal Processing

Driver

Data I/O

IRIS/Labview

Upconversion/Interpolation

Downconversion/Decimation

ADC

DAC

USRP DB

USRP DB

CTVR

SEVENTH FRAMEWORK PROGRAMME

COGEU
WHAT WAS THE QUESTION?
• What is a good experiment?
• How can an experiment be unambiguously defined?
• What output do we expect from an experiment?
• How do we control the wireless environment?
• What is a good experiment?
• How can an experiment be unambiguously defined?
• What output do we expect from an experiment?
• How do we control the wireless environment?
• A ‘good’ experiment should help with the evaluation, validation, demonstration of an idea.

• A good experiment should be
  – rigorously described so that it is
  – repeatable and
  – results should be reproducible
• But is that enough?
• But is that enough?
• How is your work/output measured?
• But is that enough?
• How is your work/output measured?
• Demos are nice, but...
  ...will they be remembered?
But is that enough?
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Publications Publications Publications
• But is that enough?
• How is your work/output measured?
• Demos are nice, but…
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• Publications Publications Publications
• 5 page conference papers + rigorous description of a wireless experiment: are they compatible?
• What is a good experiment?
• **How can an experiment be unambiguously defined?**
• What output do we expect from an experiment?
• How do we control the wireless environment?
• With great difficulty.
• With great difficulty.
• Defining the **things** being evaluated.
  – Moving from paper → Matlab → to a cognitive radio implementation.
• With great difficulty.
• Defining the **things** being evaluated.
  – Moving from paper → Matlab → to a cognitive radio implementation.
• Defining the objectives, constraints.
  – In COGEU much ambiguity has been removed as the application area is very defined:
    • Frequencies are known
    • Primary/incumbent neighbours are known
    • Some policy objectives are known
What is a good experiment?

How can an experiment be unambiguously defined?

What output do we expect from an experiment?

How do we control the wireless environment?
• That depends.
• What stage are we at?
  – Prototype Development
  – Validation and Demonstration
  – Certification
PROTOTYPING
COGEU TVWS transceiver is part of a larger system.
• What is a good experiment?
• **How an experiment can be unambiguously defined?**
• What output do we expect from an experiment?
• How do we control the wireless environment?
What do we expect this system to do?
DVB-T

Slave WSD

Master WSD

8 MHz assignment

COGEU Data Link

GEOLOCATION SPECTRUM DATABASE

Sensor

GPS Sensor

3
8 MHz assignment

DVB-T

GEOLOCATION SPECTRUM DATABASE

Master WSD

Slave WSD

COGEU Data Link

4

8 MHz assignment

GPS Sensor

Sensor
TVWS transceiver components

Rendezvous
Sensing
Geo-location
Shaping
What do we expect these components/algorithms to do?
What do we expect these components/algorithms to do?

<table>
<thead>
<tr>
<th>Phase</th>
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<th>Signal Analysis</th>
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From paper to prototype

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<td>Direct Connection</td>
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<td>Iris AWGN Channel</td>
<td>Iris</td>
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<td>6</td>
<td>Iris</td>
<td>USRP → USRP</td>
<td>Iris</td>
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SHAPING
Mind The Gap

DVB-T

8 MHz assignment

Transmit shaping
OFDM-based shaping techniques were investigated to enable:

- Efficient use of available spectrum
- Protection of incumbent users, i.e. DVB-T, PMSE users

- Cancellation Carriers
- Windowing
Transmit Shaping

- OFDM-based shaping techniques were investigated to enable:
  - Efficient use of available spectrum
  - Protection of incumbent users, i.e. DVB-T, PMSE users
- Cancellation Carriers
- Windowing

Comparison of CCs method, windowing and combination of both methods
Transmit Shaping

• OFDM-based shaping techniques were investigated to enable:
  – Efficient use of available spectrum
  – Protection of incumbent users, i.e. DVB-T, PMSE users

• Cancellation Carriers
• Windowing

<table>
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<tr>
<th>CCs per edge</th>
<th>window extension length</th>
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<td></td>
<td>0</td>
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<tr>
<td>( \mu )</td>
<td>0</td>
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<tr>
<td>( A_{SU}^1 ) (dB)</td>
<td>19.36</td>
</tr>
<tr>
<td>( A_{SU}^2 ) (dB)</td>
<td>21.5</td>
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<tr>
<td>( thr_{loss} ) (%)</td>
<td>0</td>
</tr>
<tr>
<td>( \mu )</td>
<td>0</td>
</tr>
<tr>
<td>( A_{SU}^1 ) (dB)</td>
<td>23.3</td>
</tr>
<tr>
<td>( A_{SU}^2 ) (dB)</td>
<td>24.4</td>
</tr>
<tr>
<td>( thr_{loss} ) (%)</td>
<td>2.29</td>
</tr>
<tr>
<td>( \mu )</td>
<td>0.11</td>
</tr>
<tr>
<td>( A_{SU}^1 ) (dB)</td>
<td>27.77</td>
</tr>
<tr>
<td>( A_{SU}^2 ) (dB)</td>
<td>27.75</td>
</tr>
<tr>
<td>( thr_{loss} ) (%)</td>
<td>4.57</td>
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<td>( \mu )</td>
<td>0.09</td>
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<tr>
<td>( A_{SU}^1 ) (dB)</td>
<td>31.1</td>
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<td>( A_{SU}^2 ) (dB)</td>
<td>30.48</td>
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<td>( thr_{loss} ) (%)</td>
<td>6.86</td>
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<td>( \mu )</td>
<td>0.05</td>
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<tr>
<td>( A_{SU}^1 ) (dB)</td>
<td>34.33</td>
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<tr>
<td>( A_{SU}^2 ) (dB)</td>
<td>32.27</td>
</tr>
<tr>
<td>( thr_{loss} ) (%)</td>
<td>9.14</td>
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</table>
Transmit Shaping

- Implementation in C++ in the IRIS SDR.
- Configurable OFDM-based modulator and demodulator components with inbuilt CC & Windowing

OFDM Symbol Creation Steps

1. Data for this symbol
2. Map to subcarriers
3. QAM Modulation
4. Apply Cancellation carriers
5. IFFT
6. Cyclic Extension
7. Add windowing extension
8. Incorporate into frame

Cyclic Extension

Add windowing extension

Incorporate into frame

Data for this symbol

Map to subcarriers

QAM Modulation

Apply Cancellation carriers

IFFT

Cyclic Extension

Add windowing extension

Incorporate into frame

frequency domain

time domain
Transmit Shaping

- Implementation in C++ in the IRIS SDR.
- Configurable OFDM-based modulator and demodulator components with inbuilt CC & Windowing.
Transmit Shaping

- Implementation in C++ in the IRIS SDR.
- Configurable OFDM-based modulator and demodulator components with inbuilt CC & Windowing
- Kick-started implementation with Dublin week-long workshop.
- Uses LPACK Fortran linear programming library
RENDEZVOUS
Rendezvous

- Rendezvous in a Dynamic Spectrum Access (DSA) context refers to the ability of two or more radios to meet and establish a link on a common channel.
- Embedded cyclostationary signatures.
Rendezvous

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- Embedded cyclostationary signatures.
Rendezvous
Rendezvous

- **Performance Evaluation**
  - Matlab-based simulations
  - Exponential Decay and Bad Urban (Cost 207) channel models
  - Flat-fading, frequency-selective fading, fast-fading (Jakes’s Doppler both at high frequency and at TVWS frequency)
  - 4Mhz signals using subcarrier spacing of 3GPP LTE

- **Key Metrics**
  - Time-to-rendezvous
  - Ability to detect
  - Ability to identify
  - Ability to acquire frequency
Rendezvous: Detection

<table>
<thead>
<tr>
<th>No. of features</th>
<th>Redundant Carriers</th>
<th>Overhead</th>
<th>Average $P_d$ (over all speeds) for $P_{fa} =0$, $\Delta t = 30T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 x (M=2)</td>
<td>4</td>
<td>2.07%</td>
<td>62%</td>
</tr>
<tr>
<td>2 x (M=3)</td>
<td>6</td>
<td>3.11%</td>
<td>88%</td>
</tr>
<tr>
<td>3x(M=3)</td>
<td>9</td>
<td>4.66%</td>
<td>97% (94% at $\Delta t = 20T$)</td>
</tr>
</tbody>
</table>

Exponential Decay Model
Rendezvous: Identification

- Signature Identification – finding the signal of interest
  - Fast-fading Jakes Doppler, Bad Urban
  - Carrier freq. 630MHz
  - Max. Doppler shifts – 25km/h-75km/h
  - 3-feature cyclo-signatures
  - 4MHz signal with 3GPP LTE subcarrier spacing
Rendezvous: Frequency Acquisition

- Frequency Acquisition can be used when there is no prior knowledge as to what a signature means in terms of centre frequency.

- 8MHz band of interest

- Signal of interest occupies 20% of band

\[ \Delta t = 30T, \text{ 75 km/h} \]
Rendezvous: Frequency Acquisition

- 8MHz band of interest
- Signal of interest occupies 20% of band
- $P_{\text{acq}} > 95\%$ for SNR $>6$dB
- $P_{\text{acq}} > 99.9\%$ for SNR $>12$dB
Experimentation beyond Matlab

• Extensive experimentation in Matlab
  – Especially challenging for mobile scenarios

• Reduced set implemented in Iris SDR
  – Very reduced set of conditions evaluated in reality
  – No mobile to date

• Hard (expensive?) to create challenging test environment.
Repeatable System Experimentation

• Evaluation with mature transceiver:
  – Spectrum efficiency
  – Packet error rates
  – TTR, Detection, Identification, Frequency Acquisition
  – With and without the USRPs
COMPONENTS TO SYSTEM
Experimenting with a system

Rendezvous
Sensing
Shaping
Geo-location
Integration and Experimentation

• Integration is not trivial.
  – Components go through exhaustive individual development
  – System integration takes a somewhat ‘big-bang’ approach
  – Some system behaviour can not be anticipated

• Workshops are crucial when development teams are remote.
Integration and Experimentation

LabVIEW/IRIS

USRP transmitter

USRP Sensing

Cogeu TVWS Tranceiver

Database access
What did we learn?

• The ideal Matlab transceiver is not real.
• The real USRP/Iris transceiver is not ideal.
• Moving towards reality for experimentation curtails the parameter space:
  – Constrained effective bandwidths
  – Constrained transmit power
  – Constrained host processing capabilities
• Limits the ‘graphibility’ of real-world experiments
And about experimentation?

• Repetition of performance is hard.
• Why?
  – Surmountable reasons: wrong versions of code, USRP drivers, etc.
  – Flakey reasons: changing hardware, inconsistent hardware.
  – Insurmountable reasons: the wireless environment.
MORE DEMOS
Validation sites

Aalborg

Banska Bystrica
Munich

TVWS BS

Munich
Banska Bystrica

Banska Bystrica is a extremely broken and mountainous region in the middle of Slovakia with high dense populated areas. Its average distance of 100 km from borders and geographical conditions (surrounded by hills) makes the existence of unused TV channels highly probable, and a good case study for COGEOU rural broadband scenario.
What is a good experiment?

How an experiment can be unambiguously defined?

What output do we expect from an experiment?

How do we control the wireless environment?
Test & Trial

- Clean spectrum.
- 2.4GHz dirty and noisy.
- 5GHz less so.
- Other bands.... generally illegal

- Publication of results from illegal experimentation may be problematic.
Clean Spectrum

www.testandtrial.ie
www.comreg.ie
CTVR Test & Trial

Transmit Sites

CTVR

COGEOU

2.08 GHz

2.35 GHz

25 MHz

SEVENTH FRAMEWORK PROGRAMME
<table>
<thead>
<tr>
<th>Channel</th>
<th>Centre Freq. (MHz)</th>
<th>Max ERP</th>
<th>BW (MHz)</th>
<th>Mobile</th>
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<tbody>
<tr>
<td>1</td>
<td>231.2250</td>
<td>1 W (0dBW)</td>
<td>1.75</td>
<td>Yes</td>
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<tr>
<td>2</td>
<td>233.0250</td>
<td>1 W (0dBW)</td>
<td>1.75</td>
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<tr>
<td>3</td>
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<td>1 W (0dBW)</td>
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<td>12</td>
<td>2231.0000</td>
<td>1 W (0dBW)</td>
<td>50.0</td>
<td>No</td>
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Test & Trial

NOWHERE or 90km from SOMEWHERE
Conclusions

• What is a good experiment?
• How an experiment can be unambiguously defined?
• What output do we expect from an experiment?
• How do we control the wireless environment?
Questions

Dr. Tim Forde
fordeti@tcd.ie