COGEU

Cognitive radio systems for efficient sharing of TV white spaces in European Context

COGEU is a Specific Target Research Project (**STREP**) supported by the 7th Framework Programme, Contract number: 248560

SEVENTH FRAMEWORK PROGRAMME

CTVR the telecommunications research centre

Dr. Tim Forde

SEVENTH FRAMEWORK PROGRAMME

WHAT IS COGEU?

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.

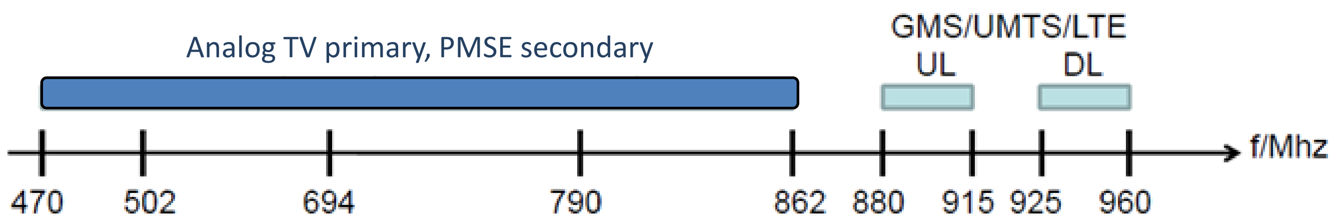
C O G EU

SEVENTH FRAMEWORK PROGRAMME

CTVR

Motivation

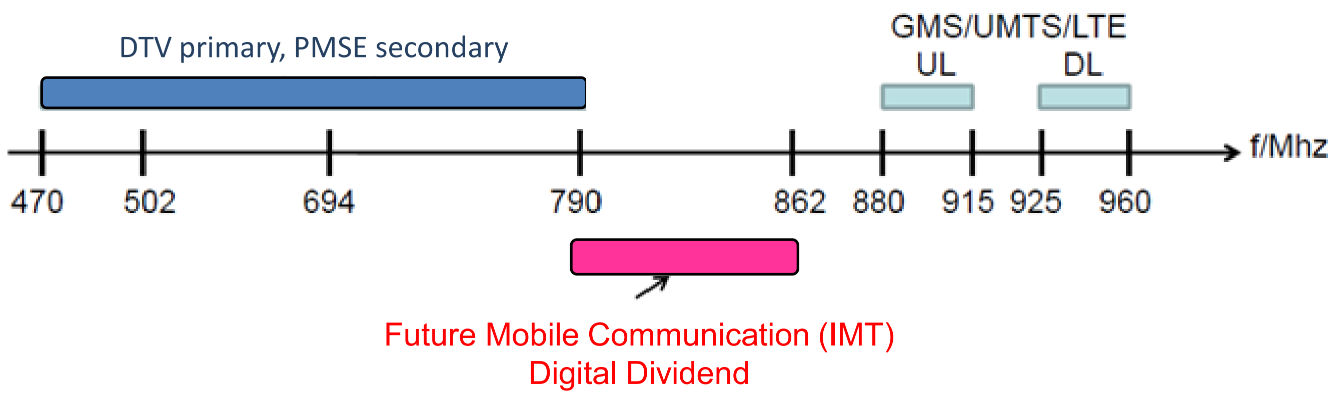
- In Europe the complete digital switch over is planned for 2012 and will open a “once in a lifetime” opportunity for the networks of the future.



Motivation

- 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 .



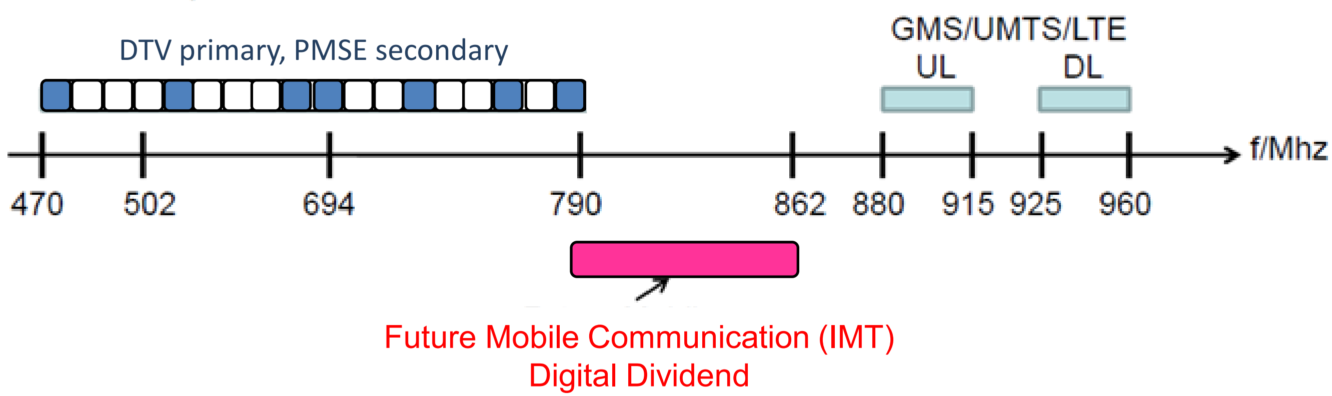
C O G EU

SEVENTH FRAMEWORK PROGRAMME

CTVR

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 ?

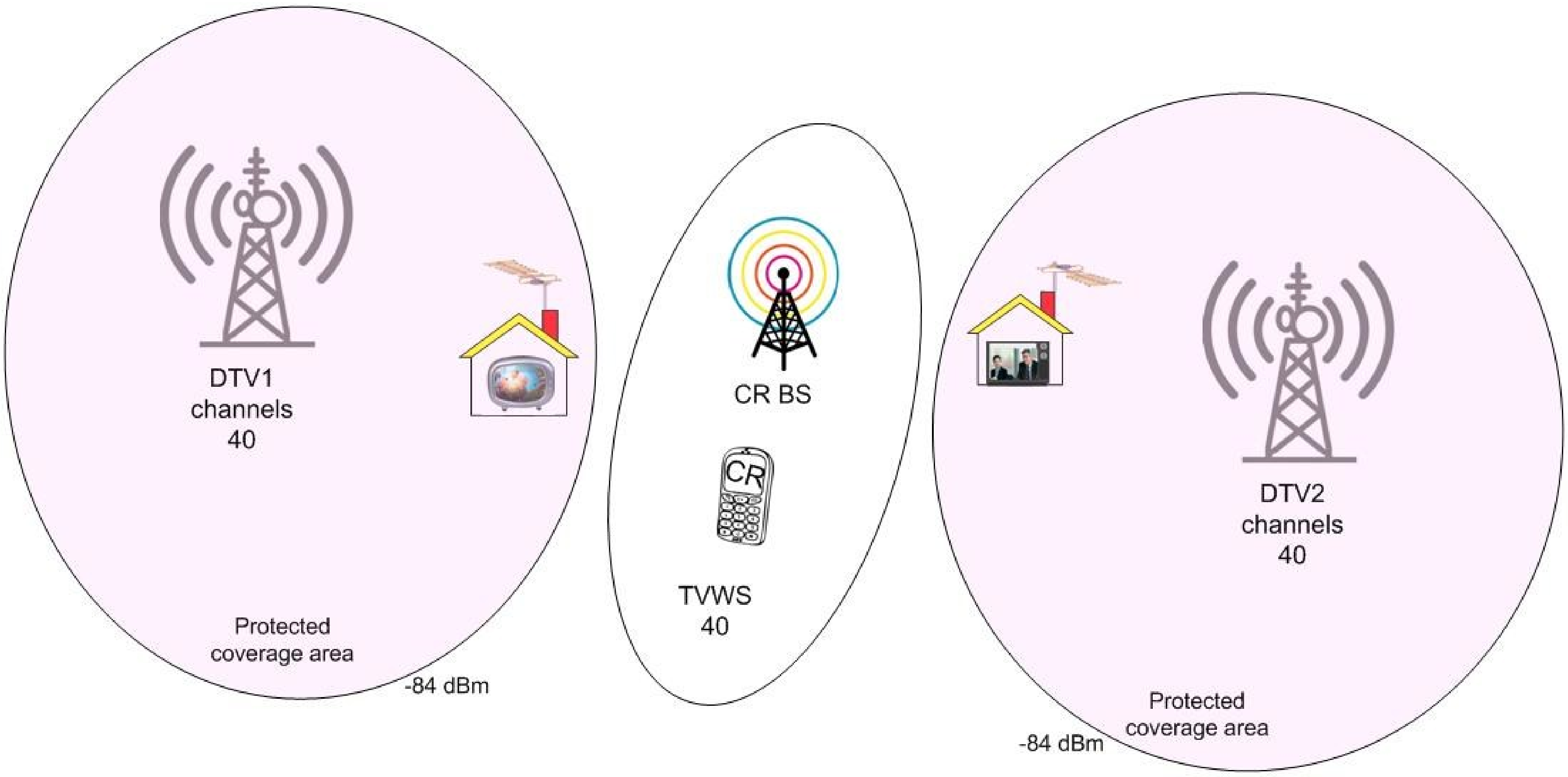


C O G EU

SEVENTH FRAMEWORK PROGRAMME

CTVR

Motivation



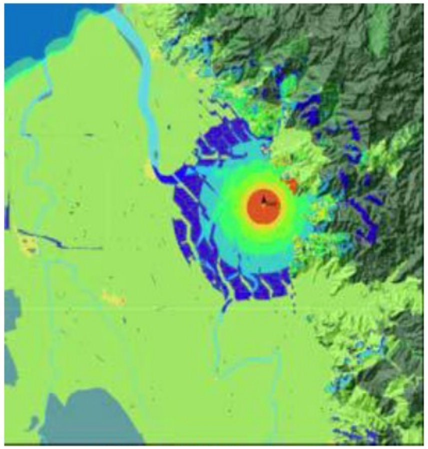
C O G EU

SEVENTH FRAMEWORK PROGRAMME

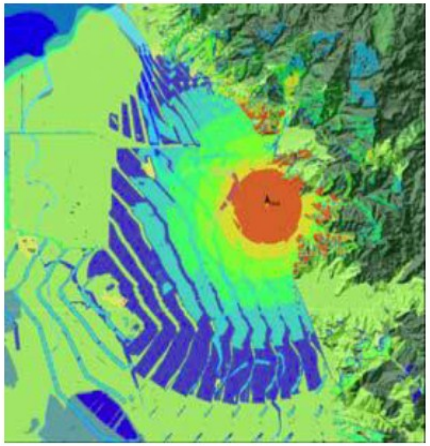
CTVR

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



2 GHz coverage



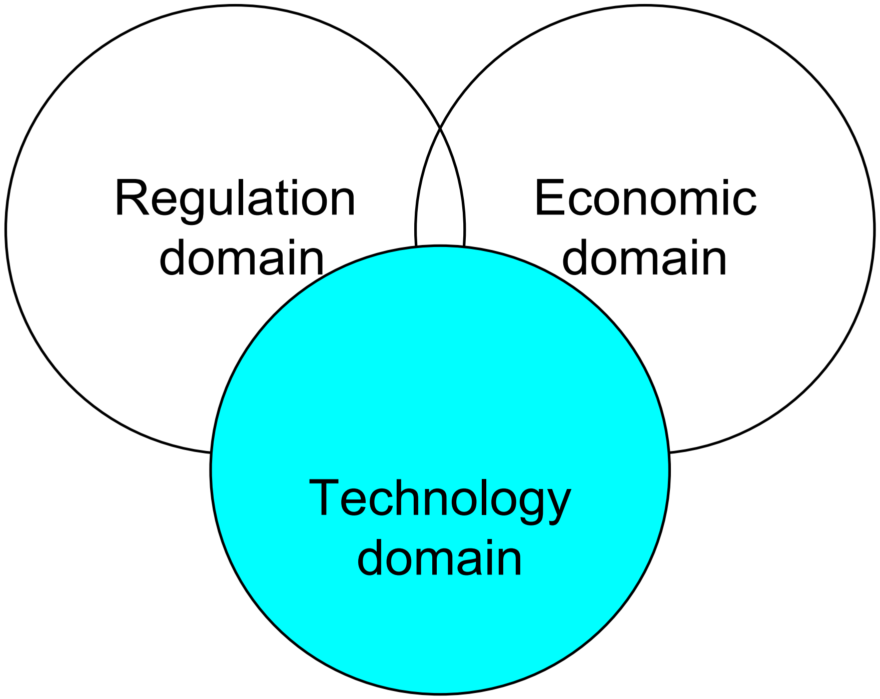
700 MHz coverage

C O G EU

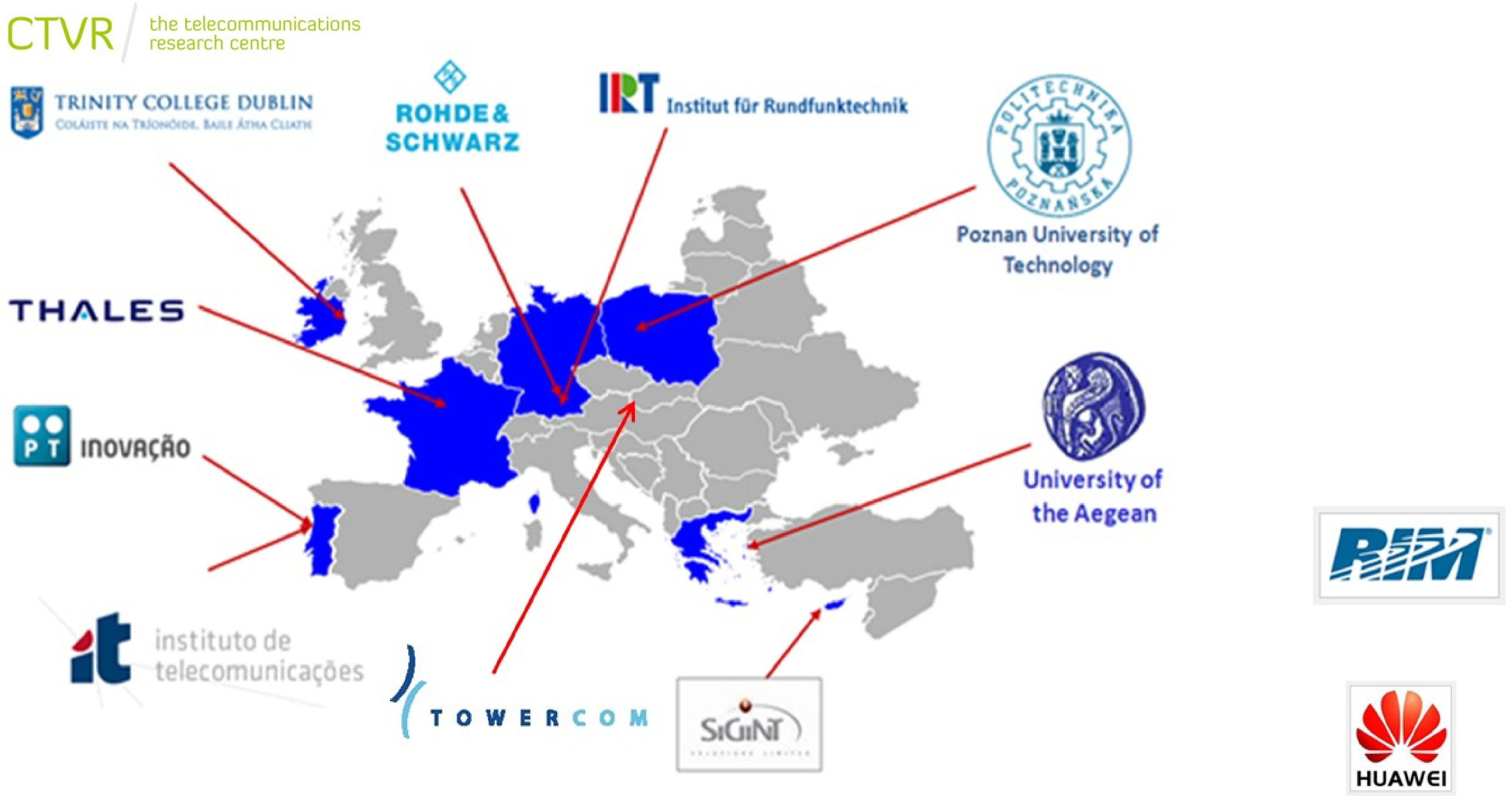
SEVENTH FRAMEWORK PROGRAMME

CTVR

COGEU domains



COGEU consortium



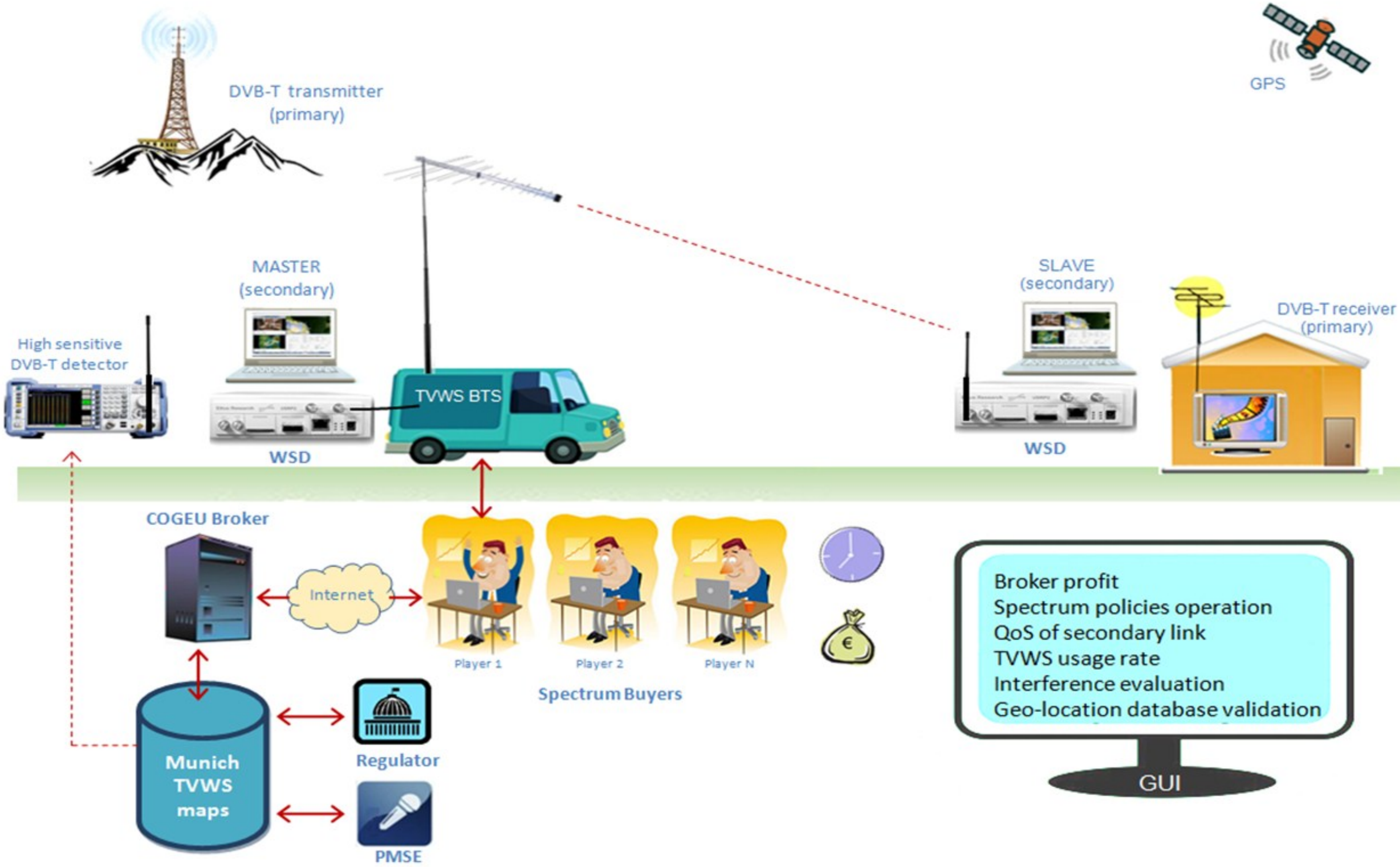
COGEU

SEVENTH FRAMEWORK PROGRAMME

CTVR

AND AT THE THE END?

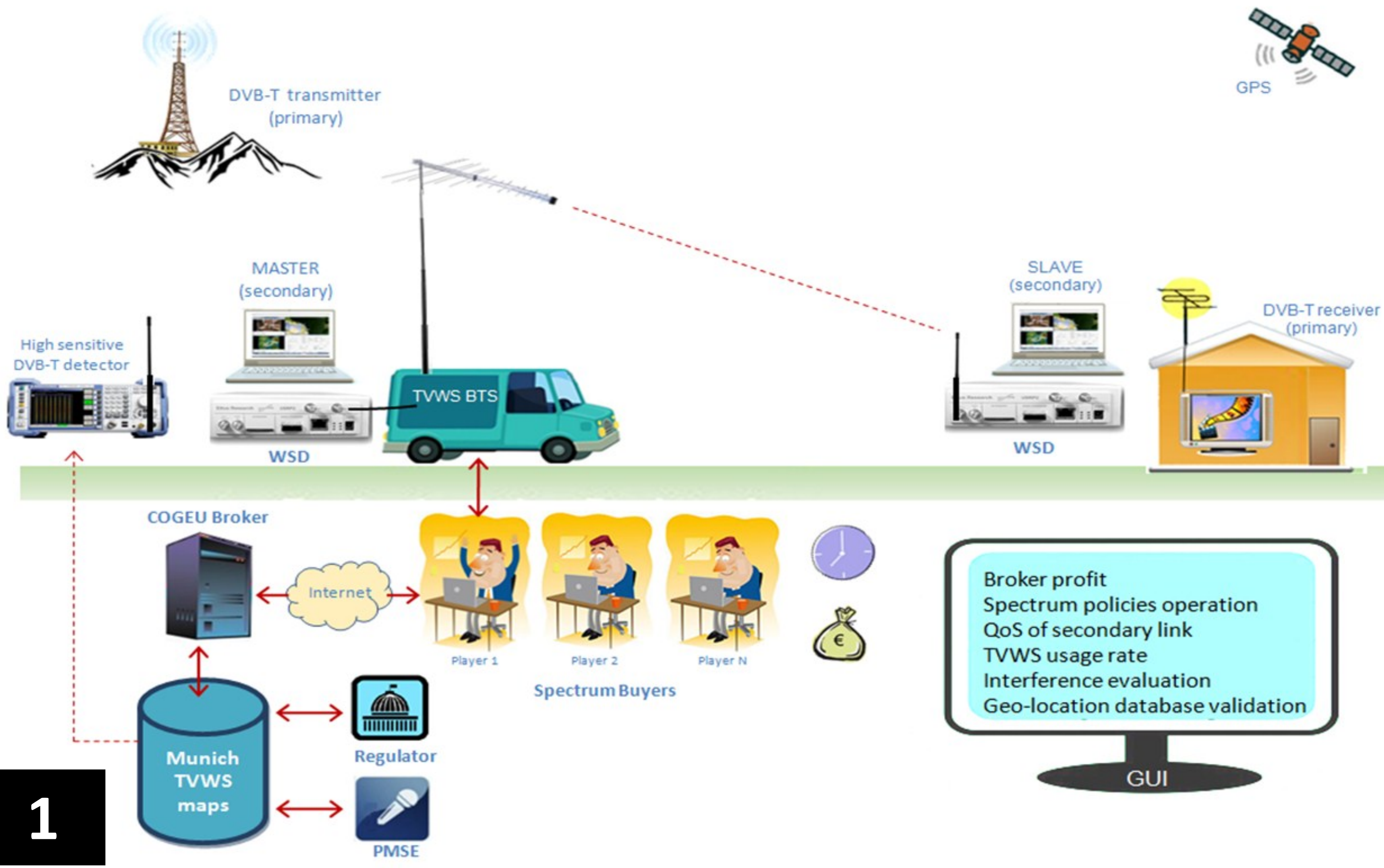
Final COGEU demo



COGEU SEVENTH FRAMEWORK PROGRAMME CTVR

TVWS database

Final COGEU demo



1

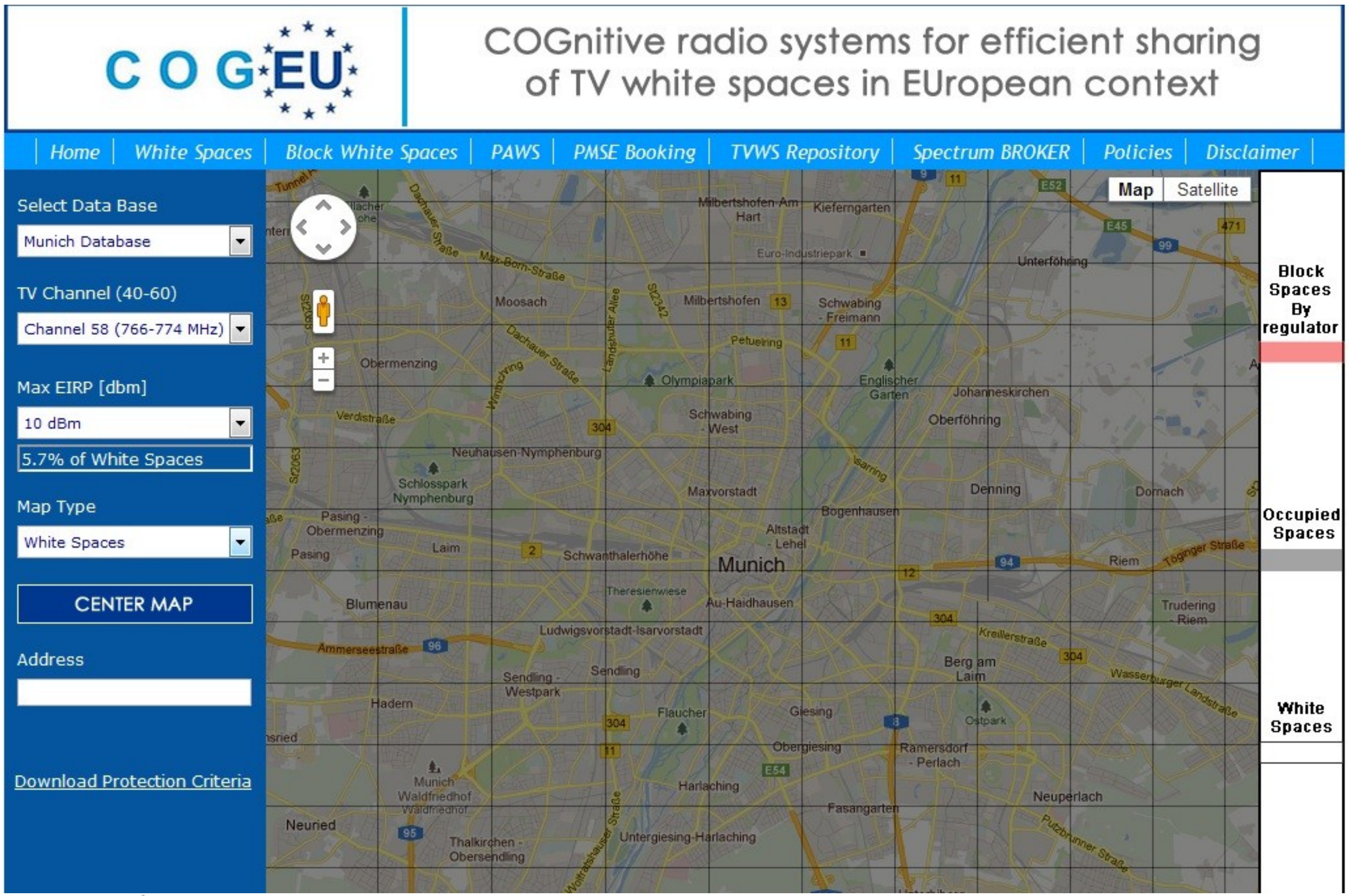
C O G EU

SEVENTH FRAMEWORK PROGRAMME

CTVR

TVWS geo-location database

Ch. 58



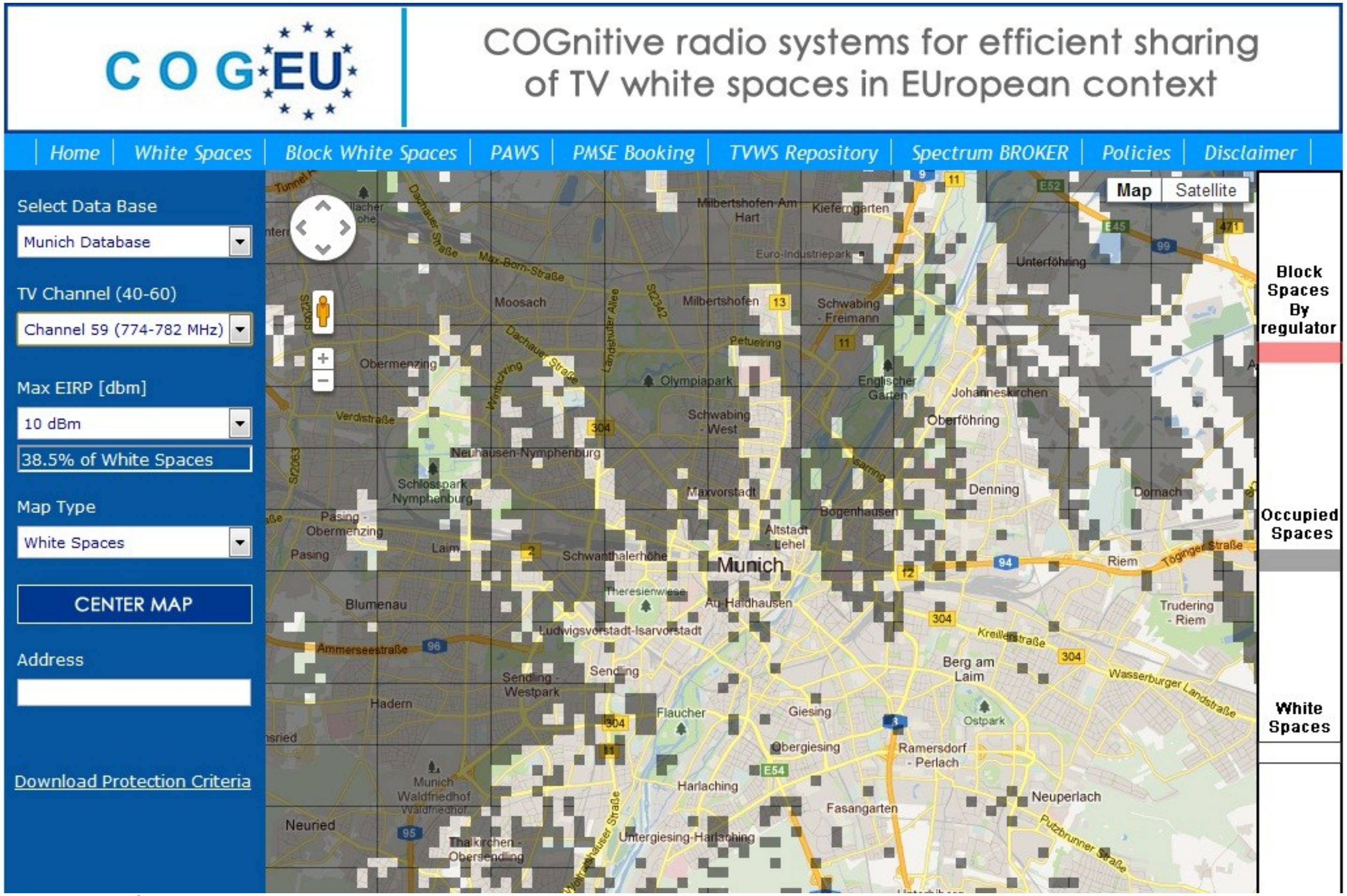
COGEU

SEVENTH FRAMEWORK PROGRAMME

CTVR

TVWS geo-location database

Ch. 59

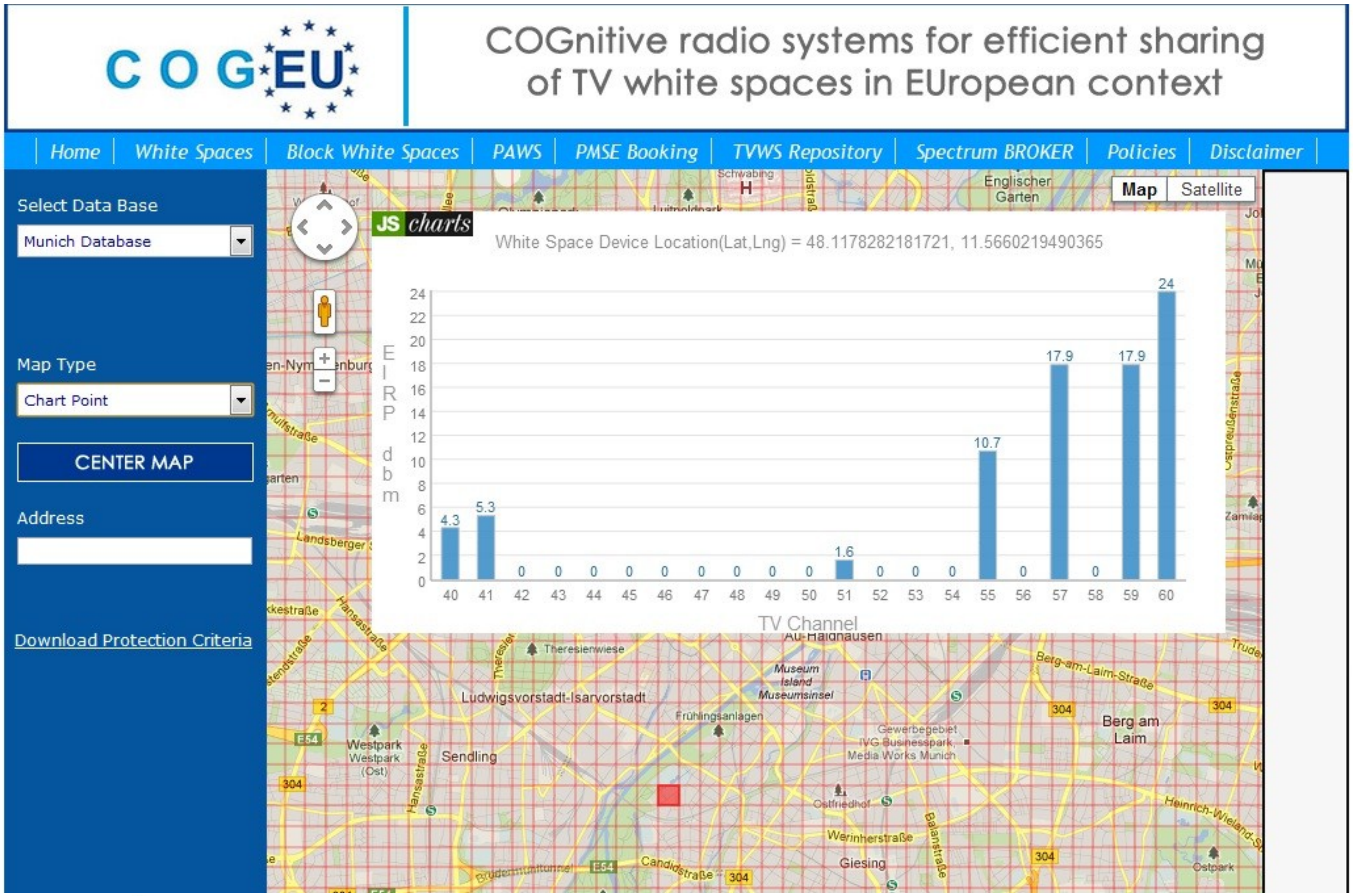


COGEU

SEVENTH FRAMEWORK PROGRAMME

CTVR

TVWS geo-location database



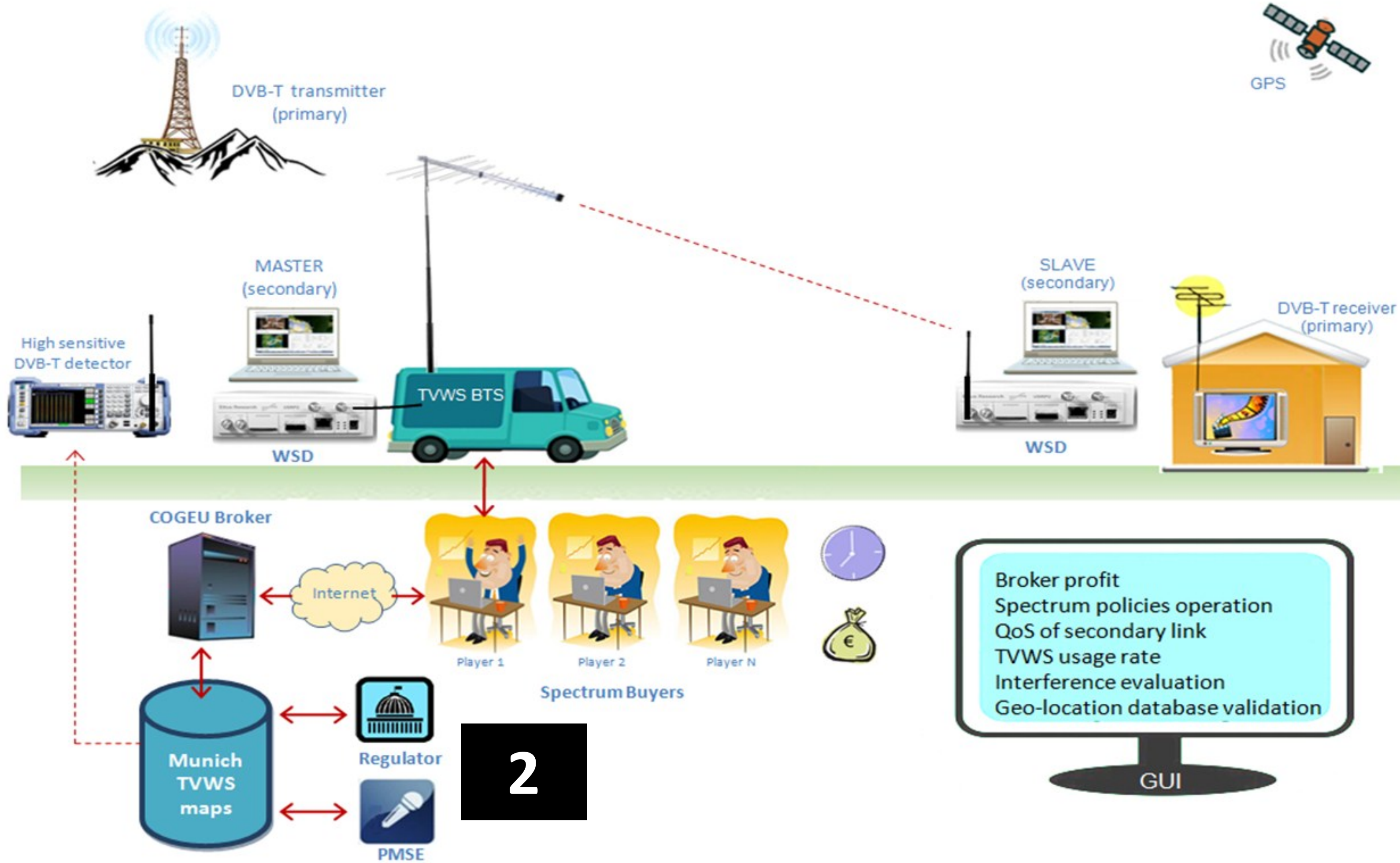
COGEU

SEVENTH FRAMEWORK PROGRAMME

CTVR

policies

Final COGEU demo



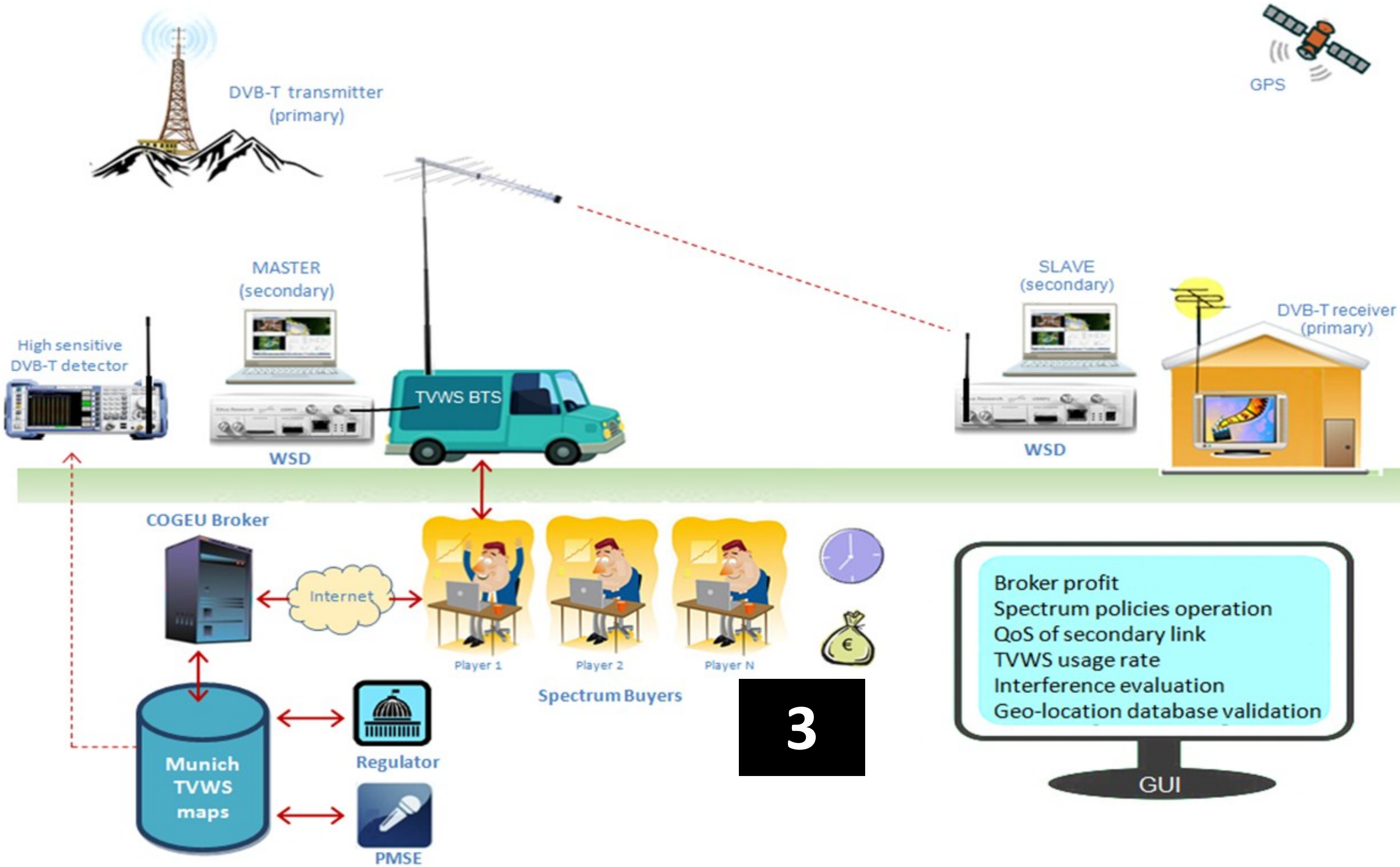
COGEU

SEVENTH FRAMEWORK PROGRAMME

CTVR

assignment

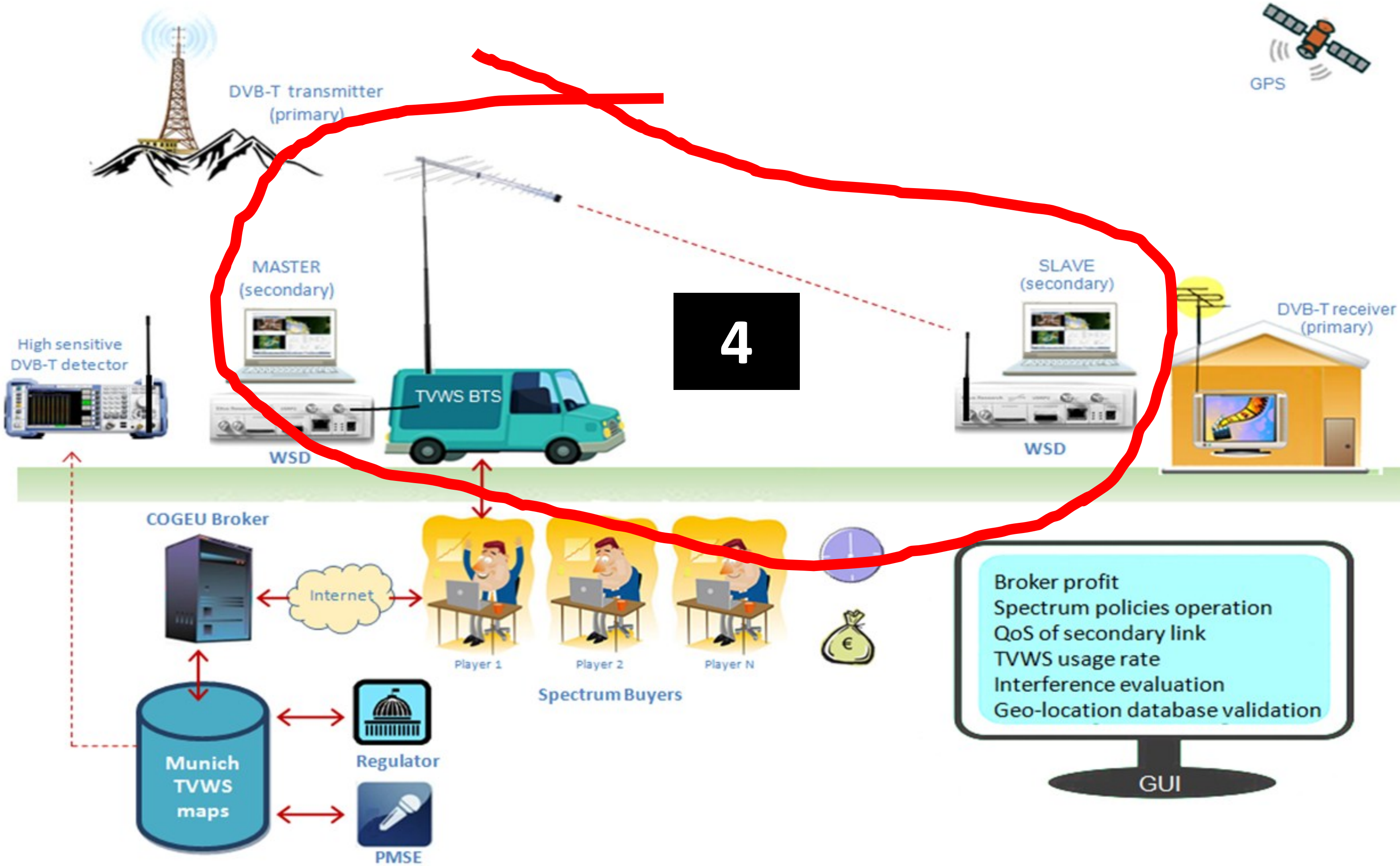
Final COGEU demo



COGEU SEVENTH FRAMEWORK PROGRAMME CTVR

transceiver

Final COGEU demo

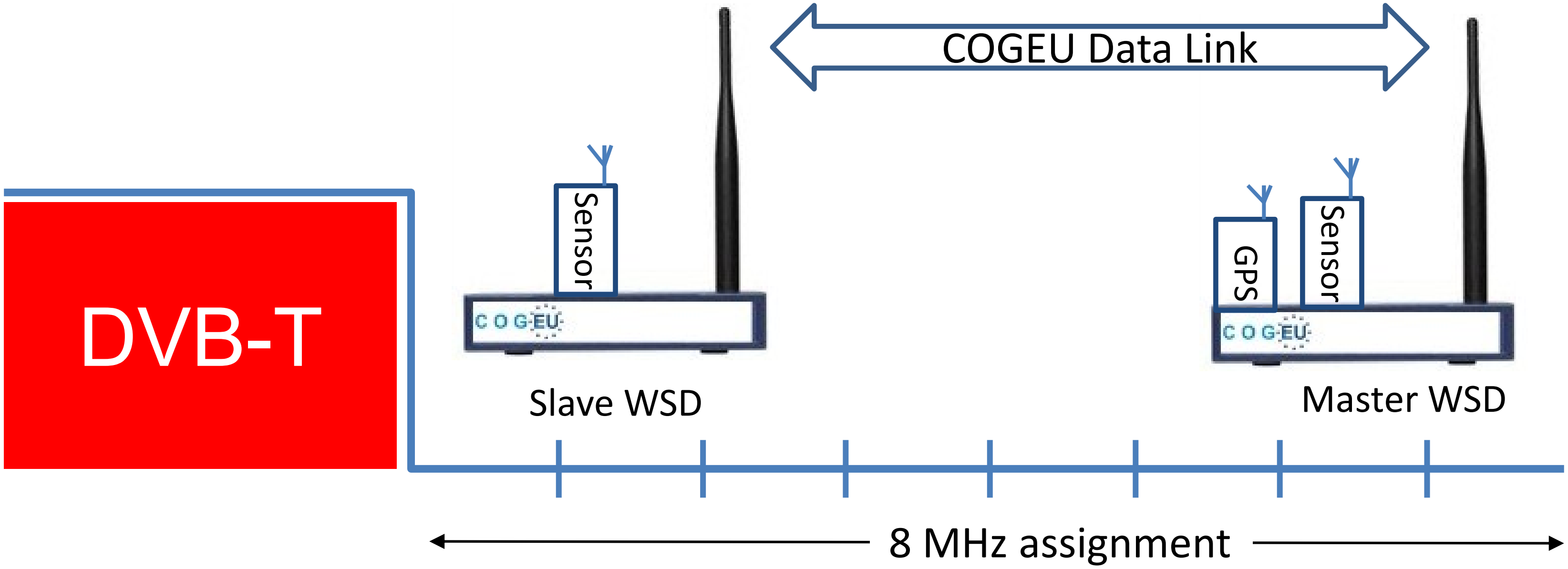


COGEU

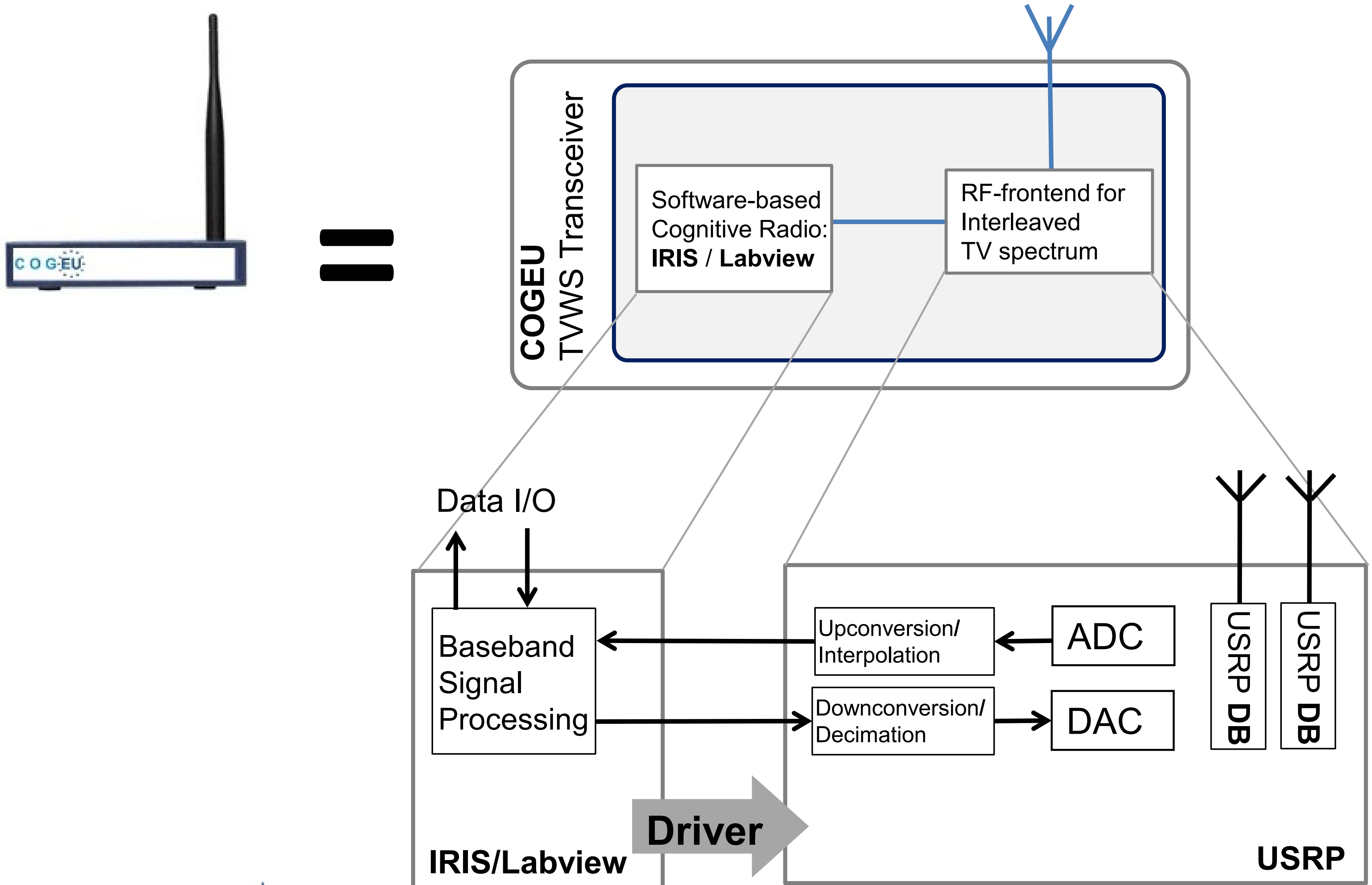
SEVENTH FRAMEWORK PROGRAMME

CTVR

TVWS transceiver



creating a node-to-node link in TVWS



COGEU
=
COGEU
TVWS Transceiver
Software-based Cognitive Radio: IRIS / Labview
RF-frontend for Interleaved TV spectrum
Data I/O
Baseband Signal Processing
Upconversion/ Interpolation
ADC
Downconversion/ Decimation
DAC
USRP DB
USRP DB
Driver
IRIS/Labview
USRP

WHAT WAS THE QUESTION?

FIRE

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

FIRE

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

COGEU SEVENTH FRAMEWORK PROGRAMME CTVR

FIRE

- 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**

FIRE

- But is that enough?

FIRE

- But is that enough?
- How is your work/output measured?

FIRE

- But is that enough?
- How is your work/output measured?
- Demos are nice, but…

  …will they be remembered?

FIRE

- But is that enough?
- How is your work/output measured?
- Demos are nice, but…

  …will they be remembered?
- Publications Publications Publications

FIRE

- But is that enough?
- How is your work/output measured?
- Demos are nice, but…

  …will they be remembered?
- Publications Publications Publications
- 5 page conference papers + rigorous description of a wireless experiment: are they compatible?

FIRE

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

FIRE

- With great difficulty.

FIRE

- With great difficulty.
- Defining the **things** being evaluated.
  - Moving from paper → Matlab → to a cognitive radio implementation.

FIRE

- 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

FIRE

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

COGEU

SEVENTH FRAMEWORK PROGRAMME

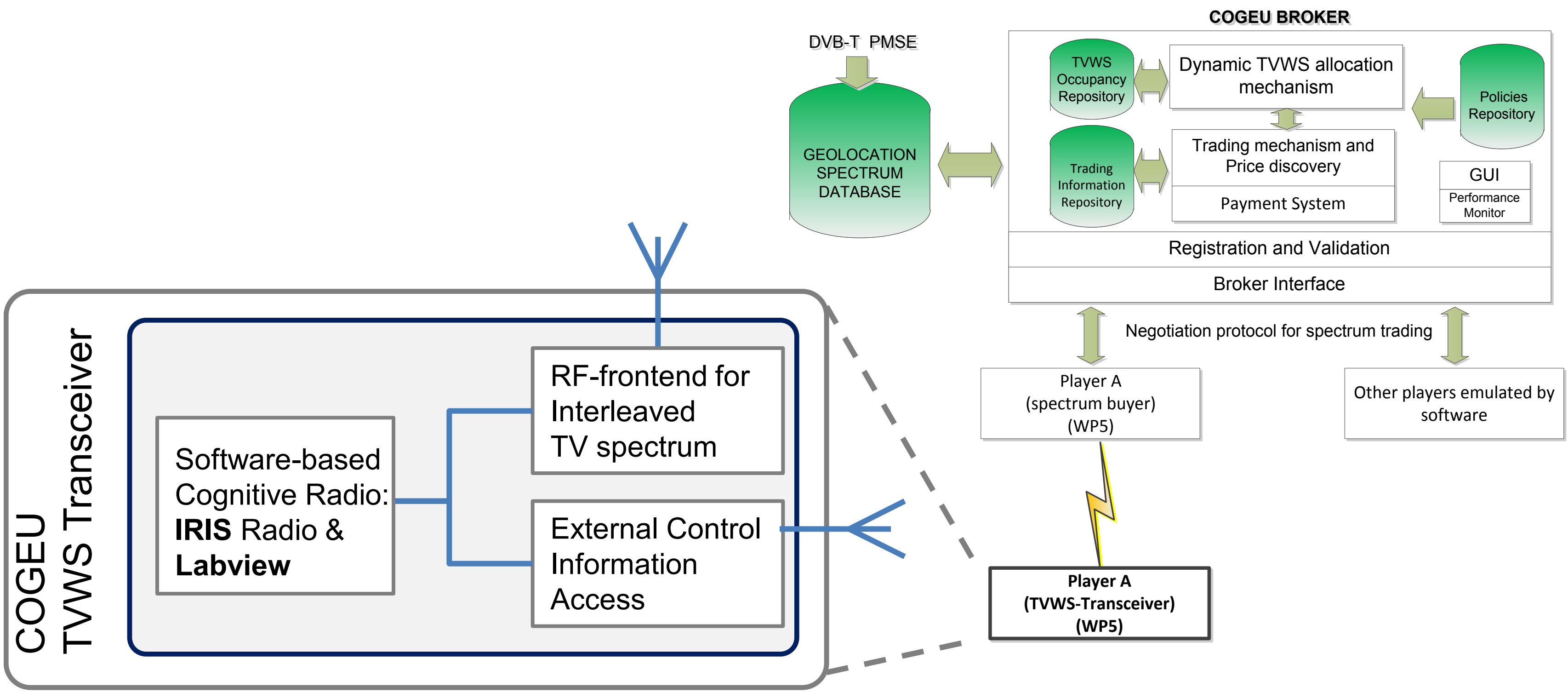
CTVR

FIRE

- That depends.
- What stage are we at?
  - Prototype Development
  - Validation and Demonstration
  - Certification

PROTOTYPING

COGEU TVWS transceiver is part of a larger system



COGEU

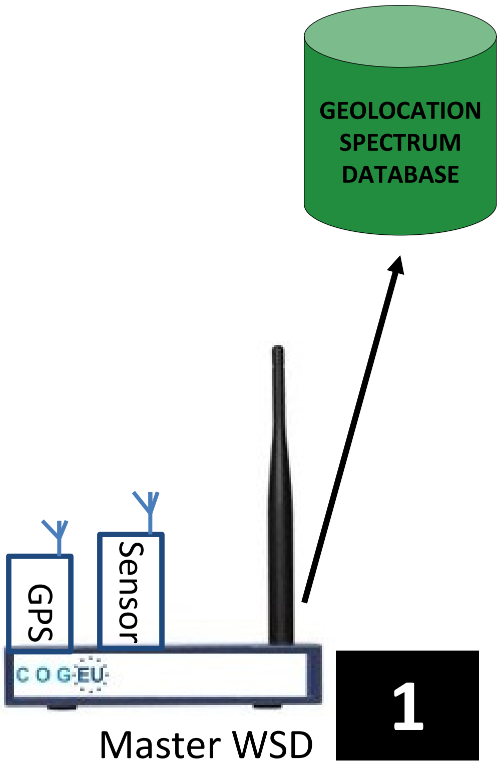
SEVENTH FRAMEWORK PROGRAMME

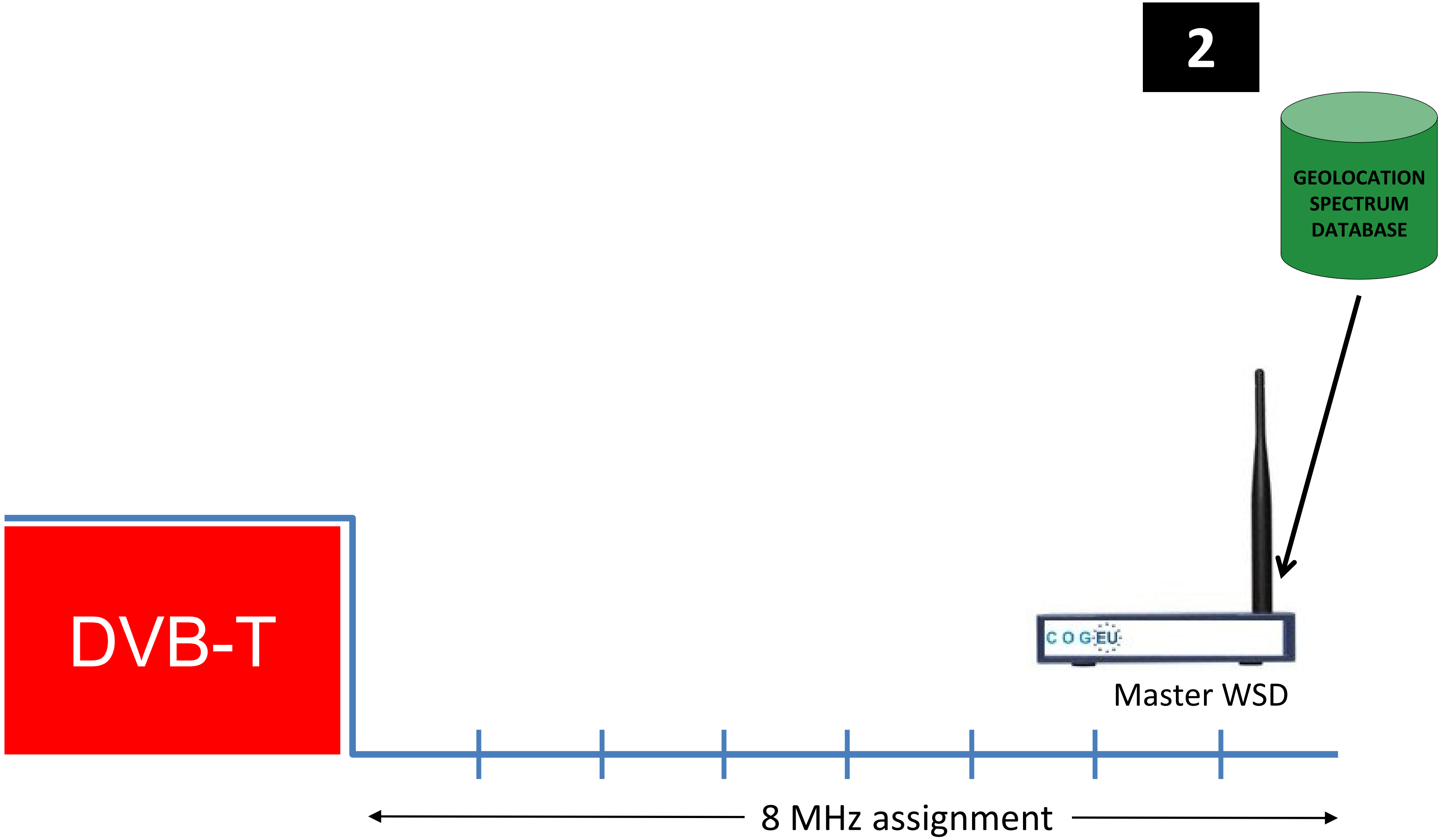
CTVR

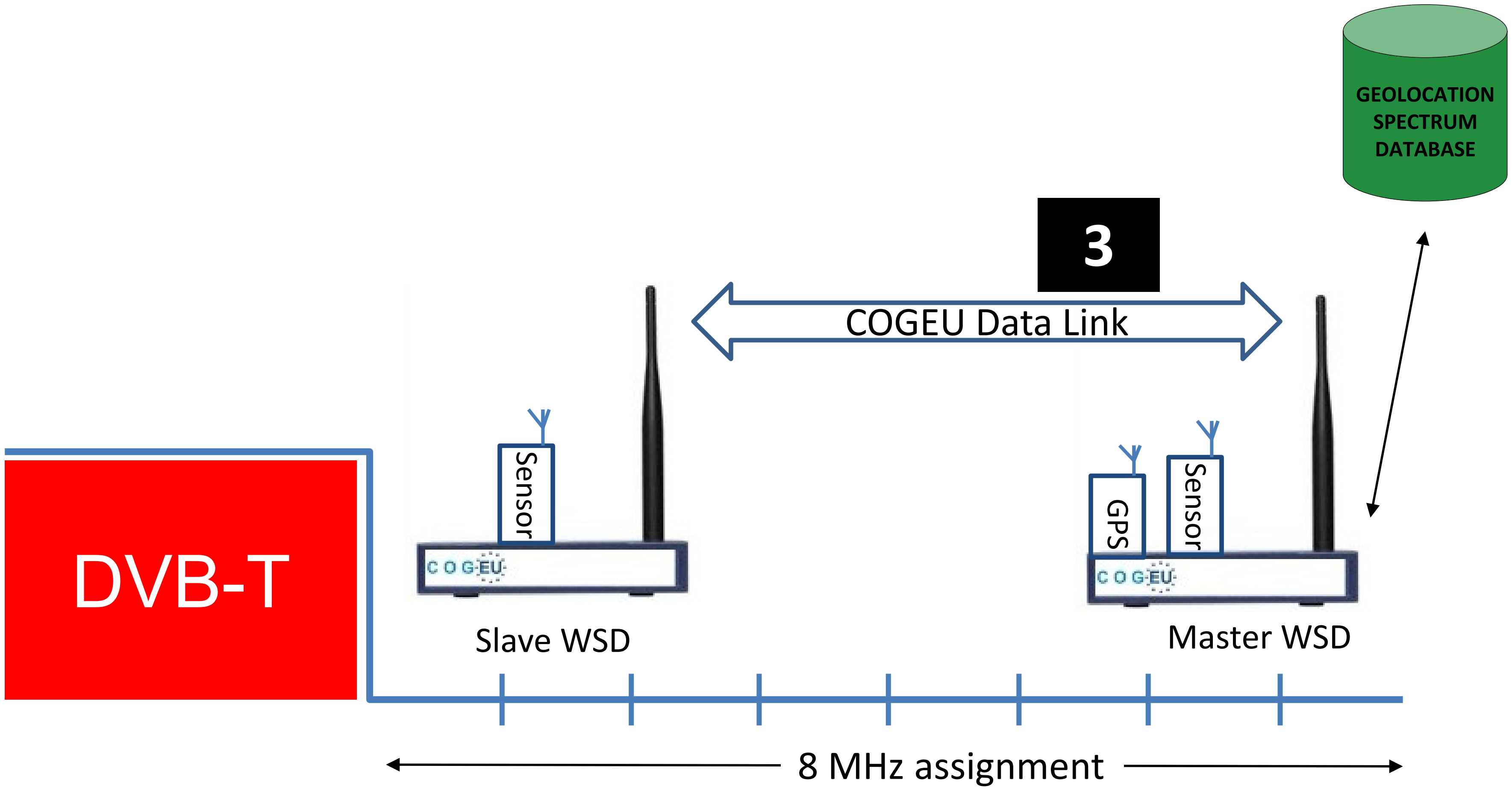
FIRE

- 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?

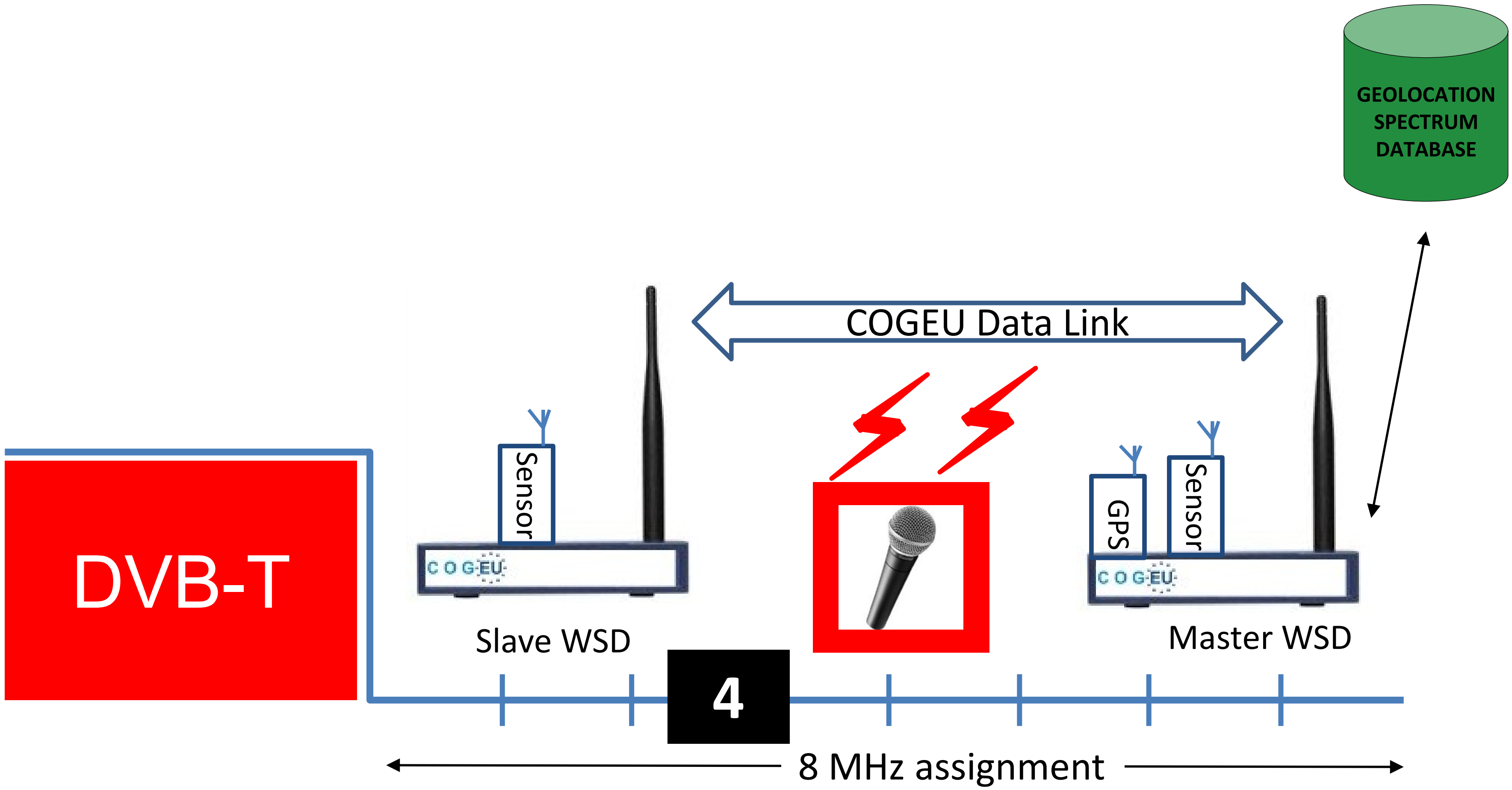
What do we expect this system to do?



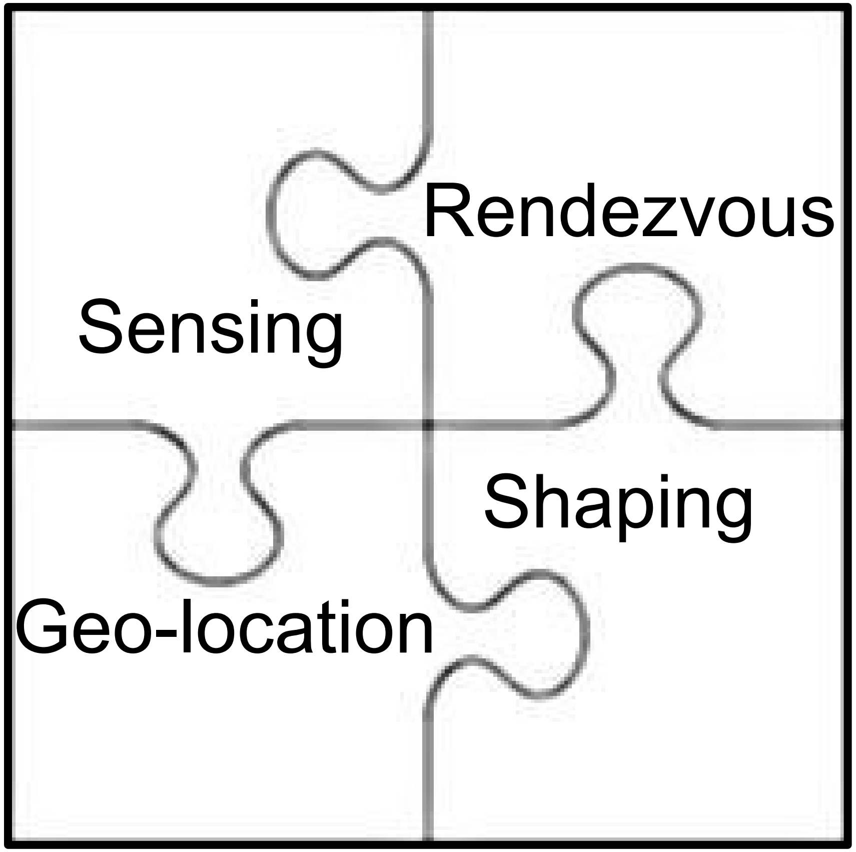

2
GEOLOCATION
SPECTRUM
DATABASE
DVB-T
Master WSD
8 MHz assignment



GEOLOCATION
SPECTRUM
DATABASE
3
COGEU Data Link
Sensor
GPS
Sensor
DVB-T
Slave WSD
Master WSD
8 MHz assignment


GEOLOCATION
SPECTRUM
DATABASE
COGEU Data Link
Sensor
GPS
Sensor
DVB-T
Slave WSD
Master WSD
4
8 MHz assignment

TVWS transceiver components



C O G EU

SEVENTH FRAMEWORK PROGRAMME

CTVR

What do we expect these components/algorithms to do?

What do we expect these components/algorithms to do?

Phase	Signal Generation	Signal Transmission &Channel	Signal Analysis
1	MATLAB	MATLAB channel models	MATLAB

From paper to prototype

Phase	Signal Generation	Signal Transmission &Channel	Signal Analysis
1	MATLAB	MATLAB channel models	MATLAB
2	MATLAB	Signal Generator → USRP	MATLAB

From paper to prototype

Phase	Signal Generation	Signal Transmission &Channel	Signal Analysis
1	MATLAB	MATLAB channel models	MATLAB
2	MATLAB	Signal Generator → USRP	MATLAB
3	MATLAB	Signal Generator → USRP	Iris

From paper to prototype

Phase	Signal Generation	Signal Transmission &Channel	Signal Analysis
1	MATLAB	MATLAB channel models	MATLAB
2	MATLAB	Signal Generator → USRP	MATLAB
3	MATLAB	Signal Generator → USRP	Iris
4	Iris	Direct Connection	Iris

From paper to prototype

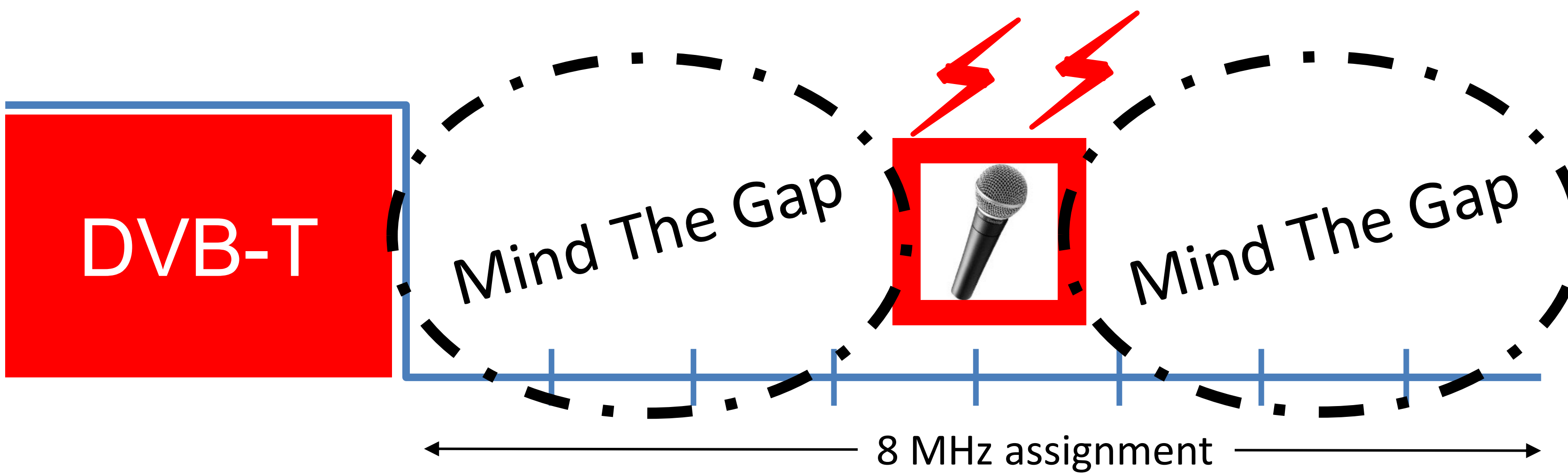
Phase	Signal Generation	Signal Transmission &Channel	Signal Analysis
1	MATLAB	MATLAB channel models	MATLAB
2	MATLAB	Signal Generator → USRP	MATLAB
3	MATLAB	Signal Generator → USRP	Iris
4	Iris	Direct Connection	Iris
5	Iris	Iris AWGN Channel	Iris

From paper to prototype

Phase	Signal Generation	Signal Transmission &Channel	Signal Analysis
1	MATLAB	MATLAB channel models	MATLAB
2	MATLAB	Signal Generator → USRP	MATLAB
3	MATLAB	Signal Generator → USRP	Iris
4	Iris	Direct Connection	Iris
5	Iris	Iris AWGN Channel	Iris
6	Iris	USRP -> USRP	Iris

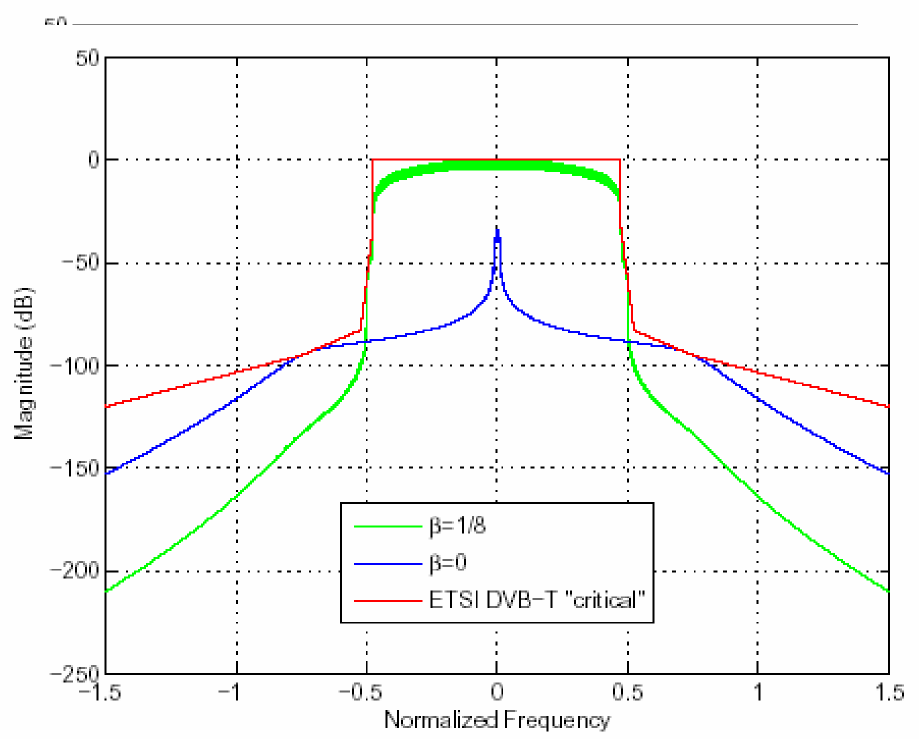
SHAPING

Transmit shaping



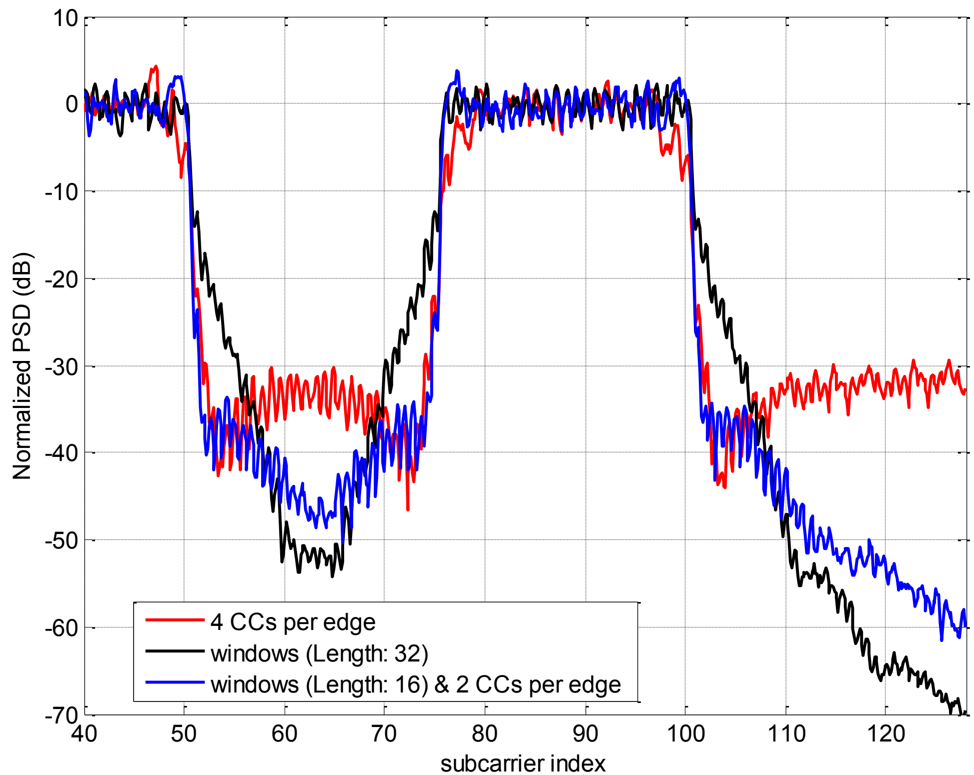
Transmit Shaping

- 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

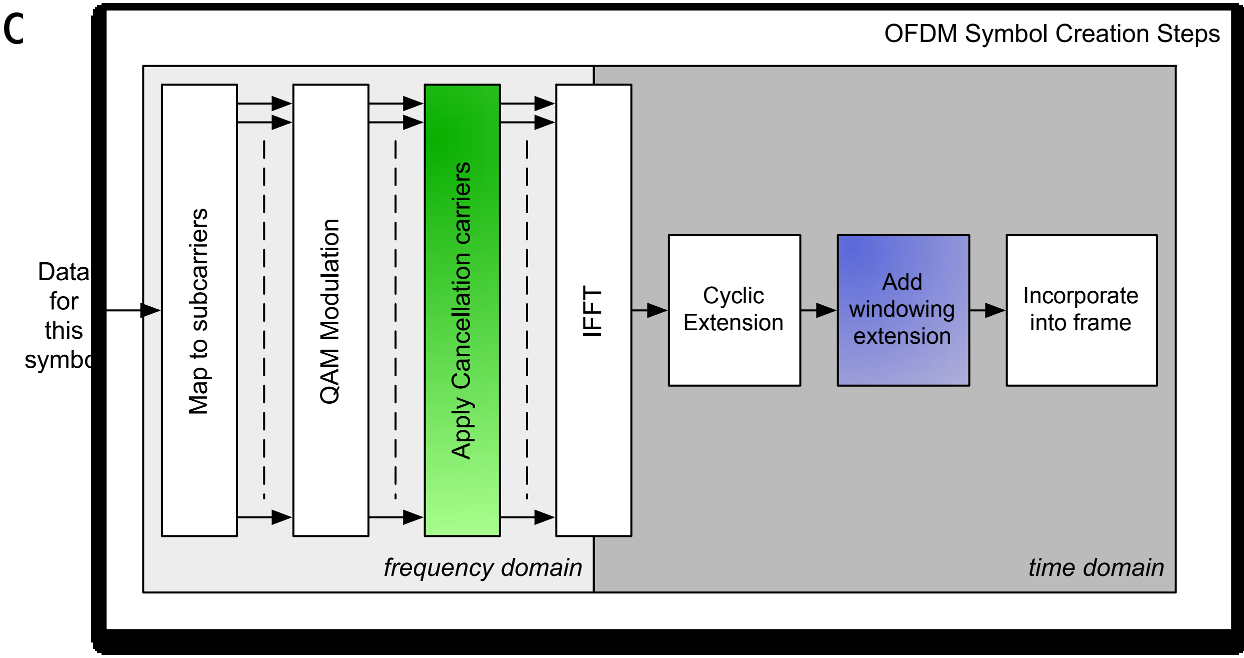
Transmit Shaping

- 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

	CCs per edge	window extension length				
		0	4	8	16	32
μ	0	0	0	0	0	0
A_{SU}^1 (dB)		19,36	20.47	21.52	23.57	26.07
A_{SU}^2 (dB)		21,5	23.44	24.54	26.77	29.11
thr_{loss} (%)		0	1.37	2.7	5.26	10
μ	1	0	0	0	0	0
A_{SU}^1 (dB)		23.3	25.14	25.75	27,5	31,2
A_{SU}^2 (dB)		24.4	27.52	28.75	30,79	34.95
thr_{loss} (%)		2.29	3.63	4.93	7.43	12.06
μ	2	0.11	0.1	0.09	0.06	0
A_{SU}^1 (dB)		27.77	29.4	32.5	39.36	49.63
A_{SU}^2 (dB)		27.75	31.48	34.65	42.06	52,54
thr_{loss} (%)		4.57	5.88	7.15	9.59	14,11
μ	3	0.09	0.05	0.03	0.015	0
A_{SU}^1 (dB)		31.1	35.41	38.7	46.69	51.31
A_{SU}^2 (dB)		30.48	36.88	40.95	49.15	54.5
thr_{loss} (%)		6,86	8.13	9.37	11.76	16.17
μ	4	0.05	0.03	0.021	0.005	0.0028
A_{SU}^1 (dB)		34.33	39.14	43.43	50.81	53.18
A_{SU}^2 (dB)		32.27	39.97	45.55	52.82	56.07
thr_{loss} (%)		9.14	10.39	11.6	13.92	18.23

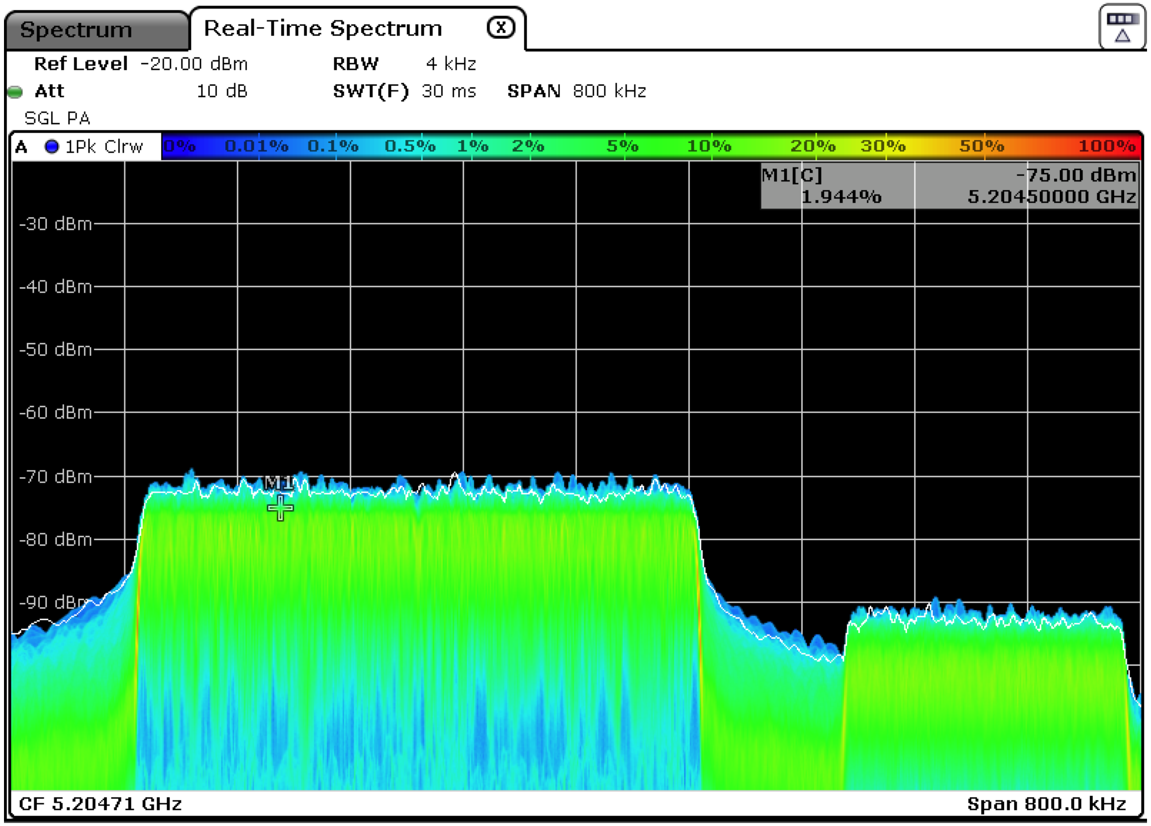
Transmit Shaping

- 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



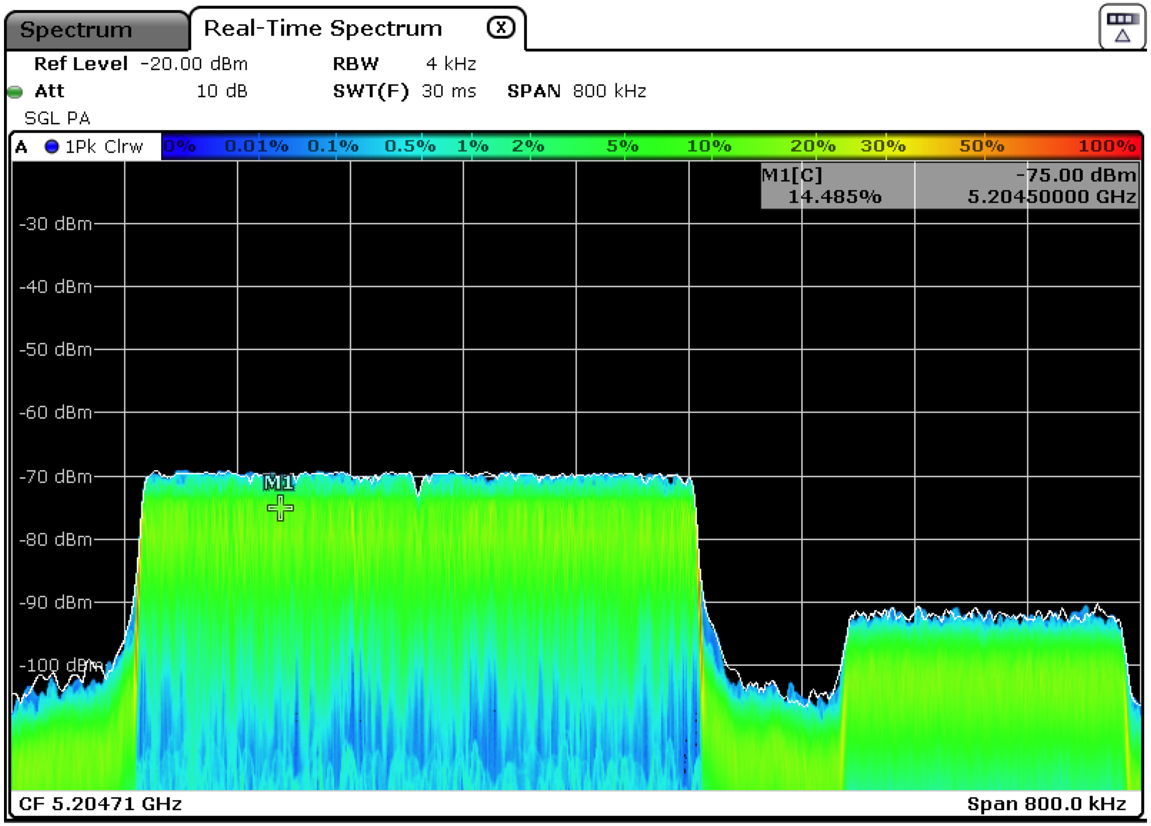
COGEU

SEVENTH FRAMEWORK PROGRAMME

CTVR

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



COGEU

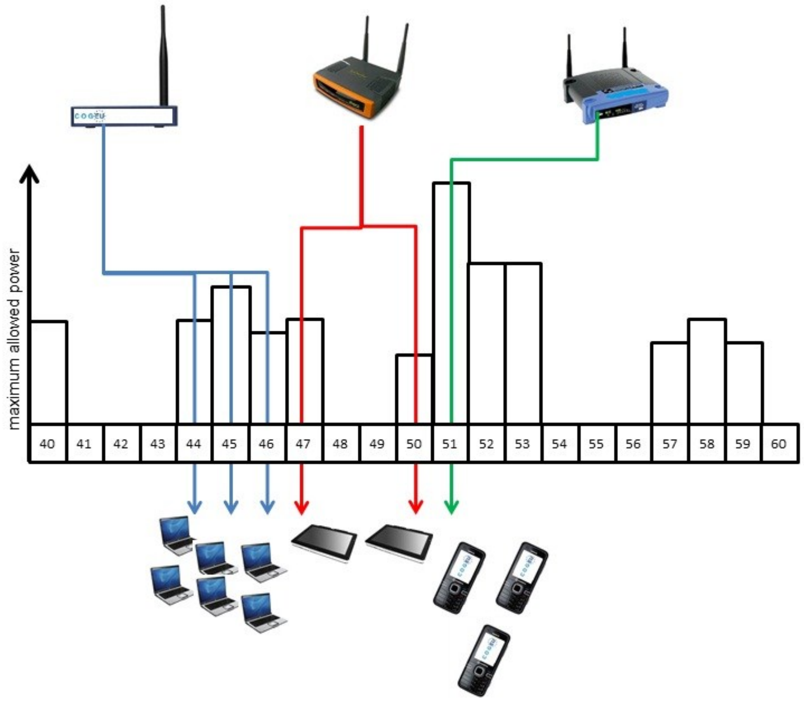
SEVENTH FRAMEWORK PROGRAMME

CTVR

RENDEZVOUS

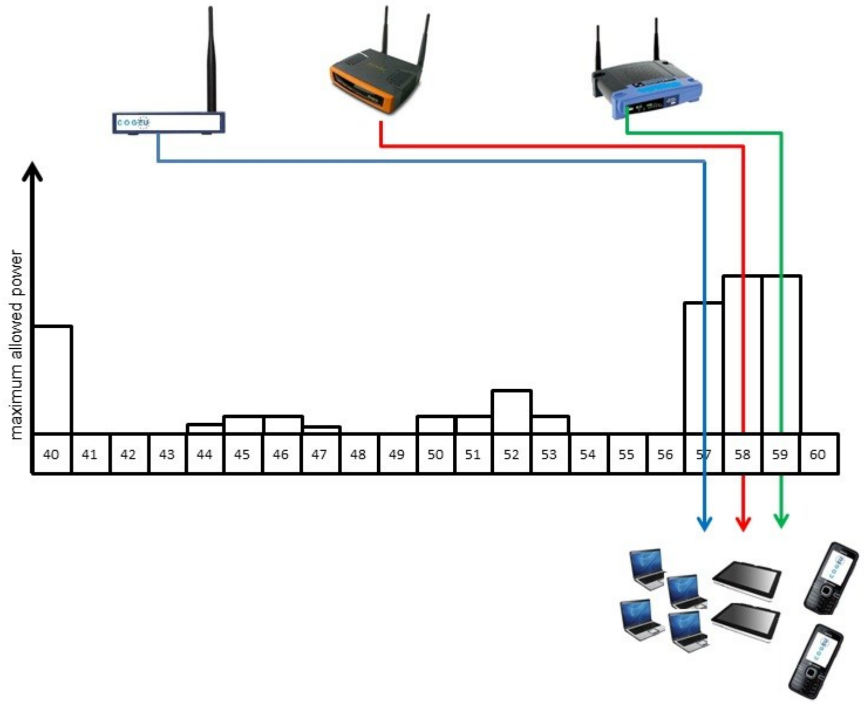
Rendezvous

- 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

- 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.



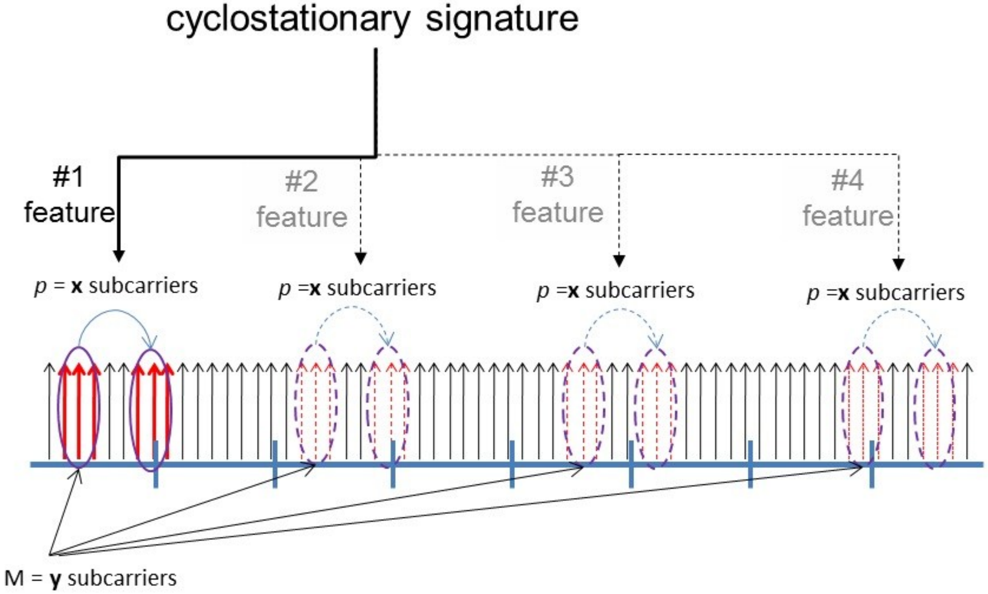
COGEU

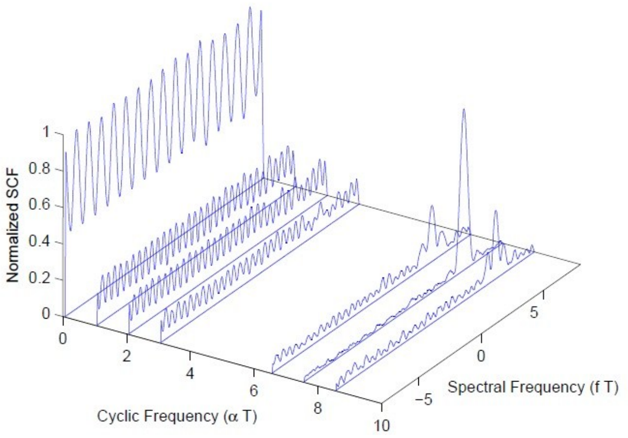
SEVENTH FRAMEWORK PROGRAMME

CTVR

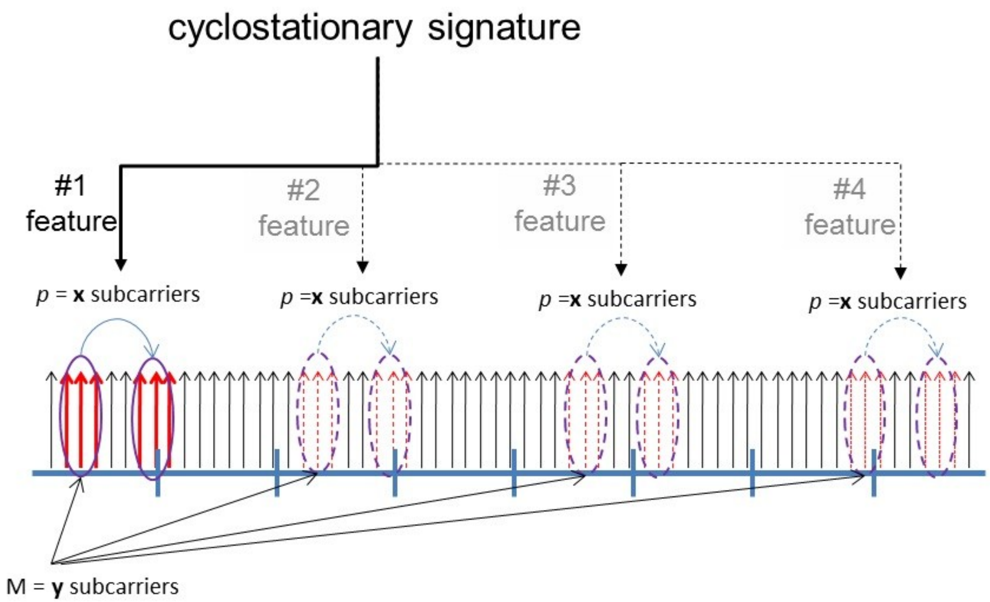
Rendezvous

- 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.

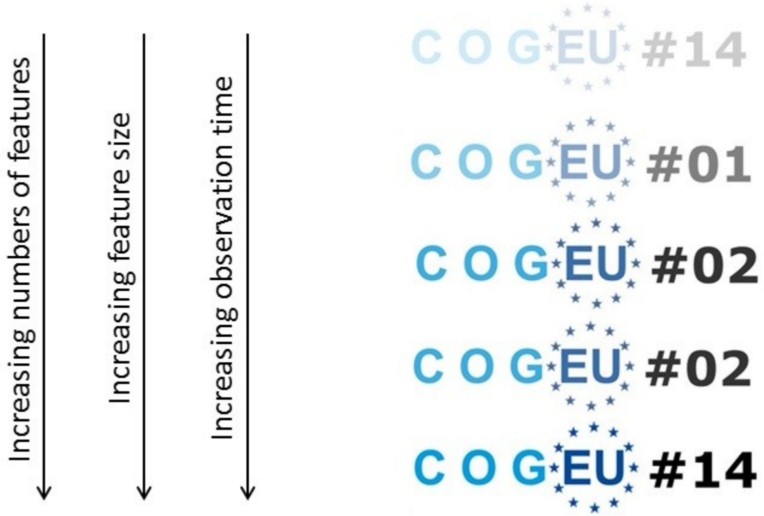




Rendezvous



cyclostationary signature
#1 feature
#2 feature
#3 feature
#4 feature
p = x subcarriers
p =x subcarriers
p =x subcarriers
p =x subcarriers
M = y subcarriers



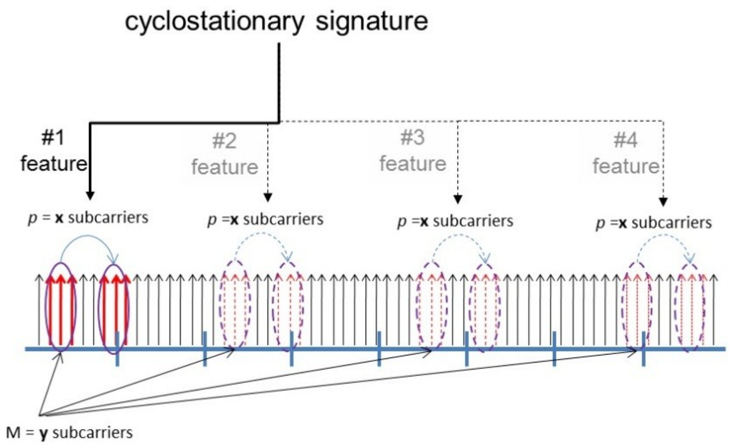
Increasing numbers of features
Increasing feature size
Increasing observation time
COGEU #14
COGEU #01
COGEU #02
COGEU #02
COGEU #14

Rendezvous

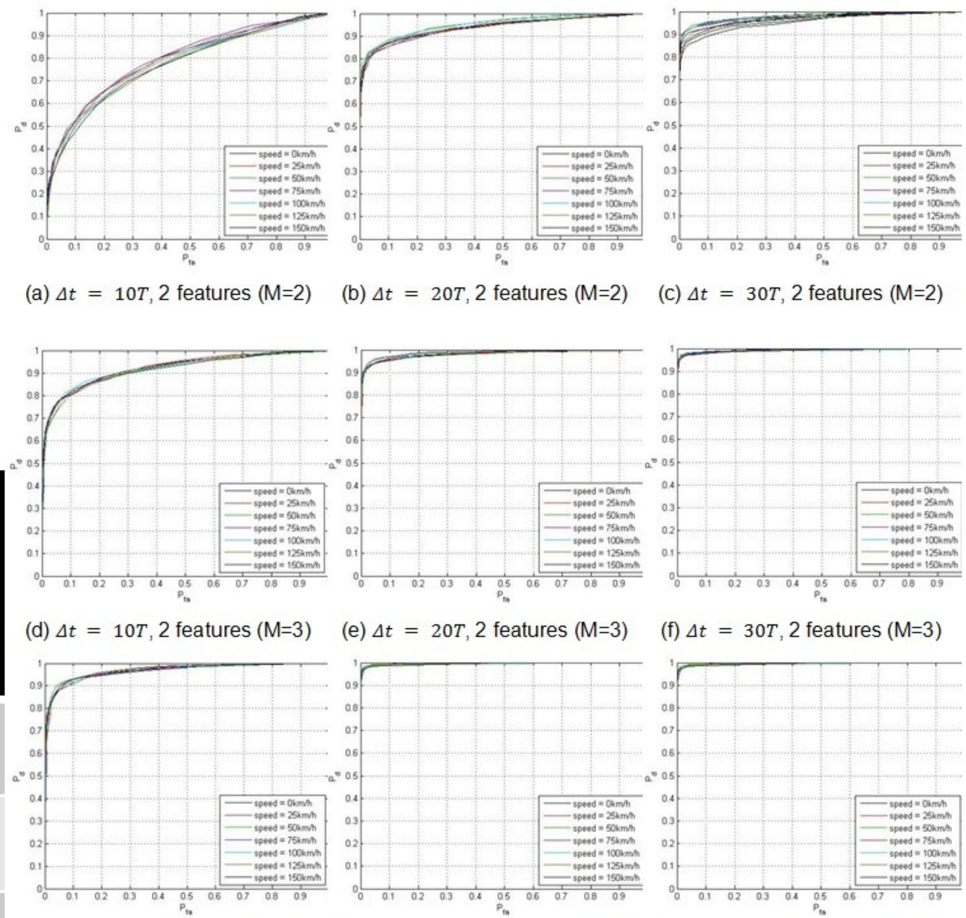
- Performance Evaluation
  - Matlab-based simulations
  - Exponential Decay and Bad Urban (Cost 207) channel models
  - Flat-fading, frequency-selective fading, fast-fading (Jakes's Doppler both at high frequency and at TVWS frequency)
  - 4Mhz signals using subcarrier spacing of 3GPP LTE

- Key Metrics
  - Time-to-rendezvous
  - Ability to detect
  - Ability to identify
  - Ability to acquire frequency

Rendezvous: Detection



No. of features	Redundant Carriers	Overhead	Average P_d (over all speeds) for P_{fa} =0, Δt = 30T
2 x (M=2)	4	2.07%	62%
2 x (M=3)	6	3.11%	88%
3x(M=3)	9	4.66%	97% (94% at Δt = 20T)



(a) $\Delta t = 10T$, 2 features (M=2) (b) $\Delta t = 20T$, 2 features (M=2) (c) $\Delta t = 30T$, 2 features (M=2)

(d) $\Delta t = 10T$, 2 features (M=3) (e) $\Delta t = 20T$, 2 features (M=3) (f) $\Delta t = 30T$, 2 features (M=3)

(g) $\Delta t = 10T$, 3 features (M=3) (h) $\Delta t = 20T$, 3 features (M=2) (i) $\Delta t = 30T$, 3 features (M=3)

Exponential Decay Model

COGEU

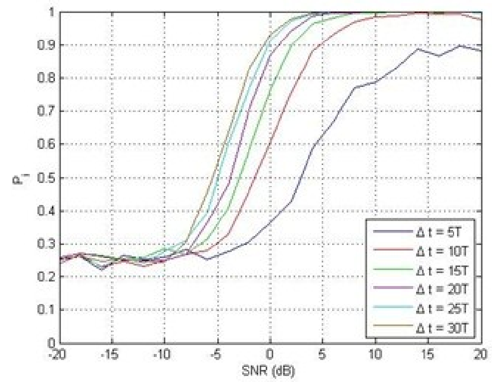
SEVENTH FRAMEWORK PROGRAMME

CTVR

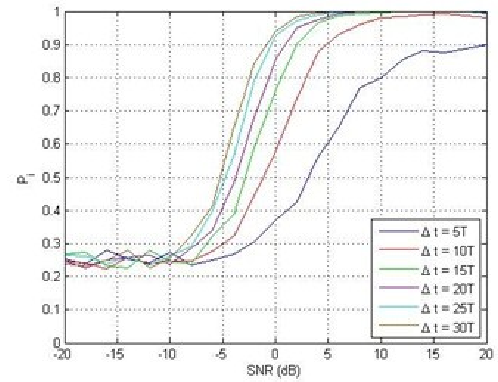
Rendezvous: Identification

- 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

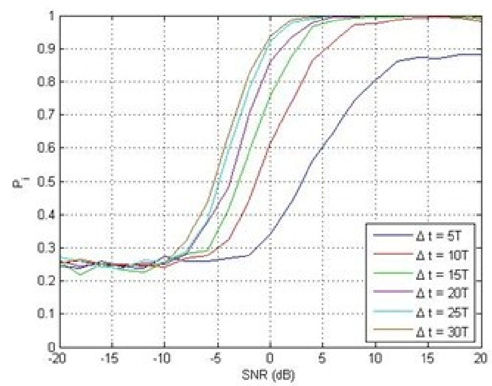
    subcarrier spacing



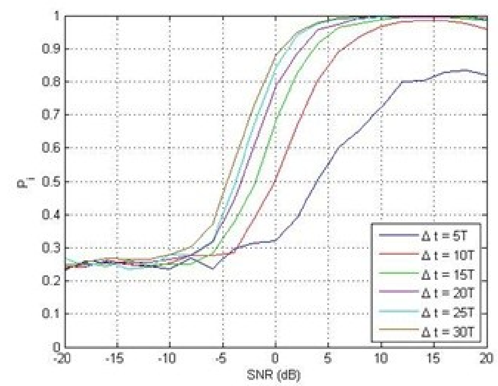
(a) quasi-static (0 km/h)



(b) 25 km/h



(c) 50 km/h



(d) 75 km/h

COGEU

SEVENTH FRAMEWORK PROGRAMME

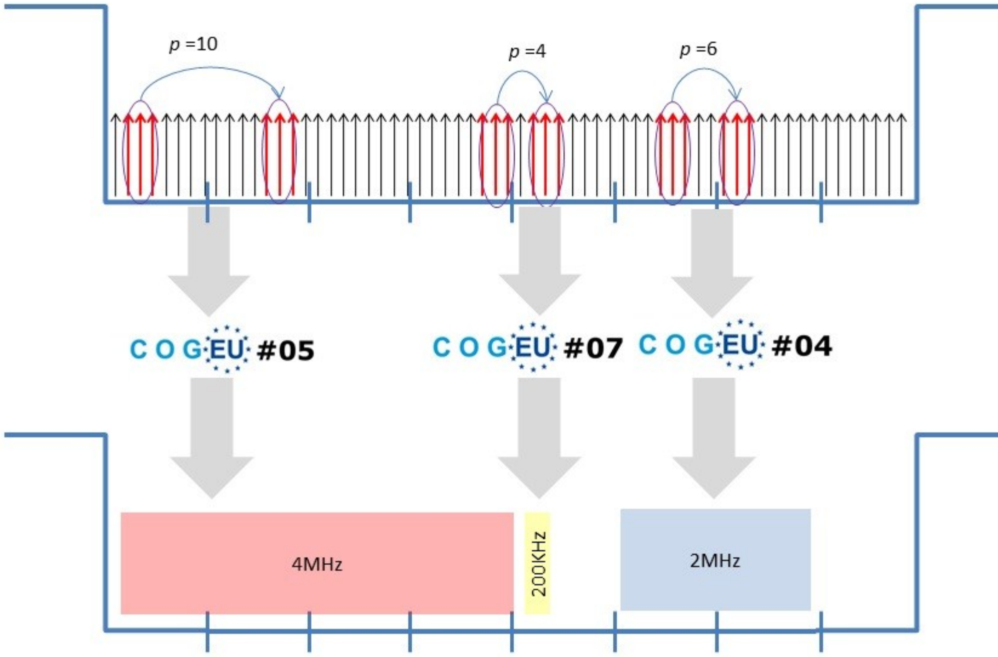
CTVR

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

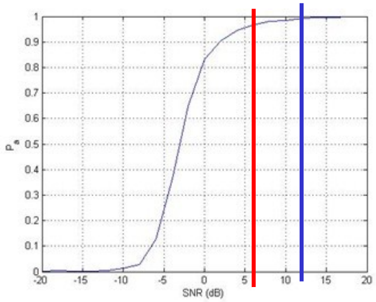


(e) $\Delta t = 30T$, 75 km/h

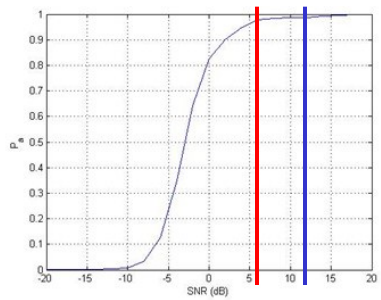
Rendezvous: Frequency Acquisition

- 8MHz band of interest
- Signal of interest occupies 20% of band

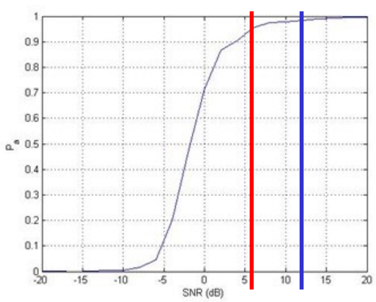
- P_{acq} > 95% for SNR >6dB
- P_{acq} > 99.9% for SNR >12dB



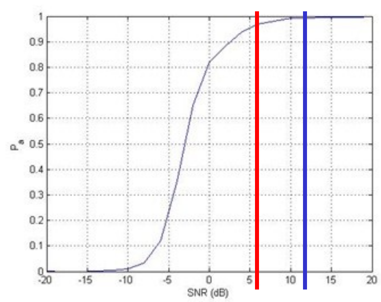
(a) $\Delta t = 30T$, quasi-static (0km/h)



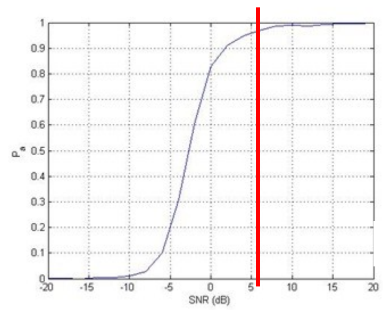
(b) $\Delta t = 30T$, 25km/h



(c) $\Delta t = 20T$, 50 km/h



(d) $\Delta t = 30T$, 50 km/h



(e) $\Delta t = 30T$, 75 km/h

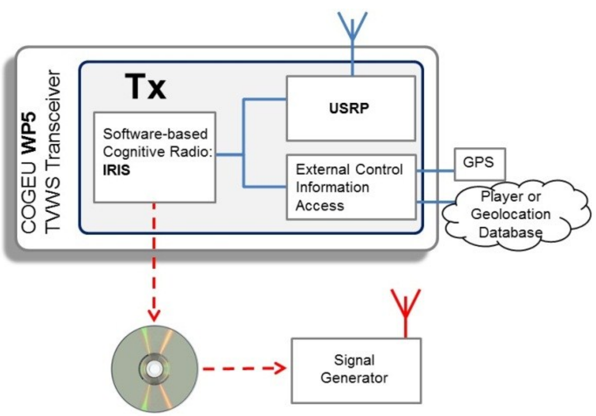
Experimentation beyond Matlab

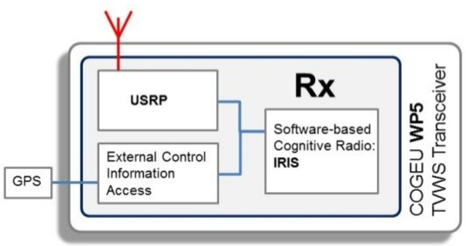
- Extensive experimentation in Matlab
  - Especially challenging for mobile scenarios
- Reduced set implemented in Iris SDR
  - Very reduced set of conditions evaluated in reality
  - No mobile to date

- Hard (expensive?) to create challenging test environment.

Repeatable System Experimentation

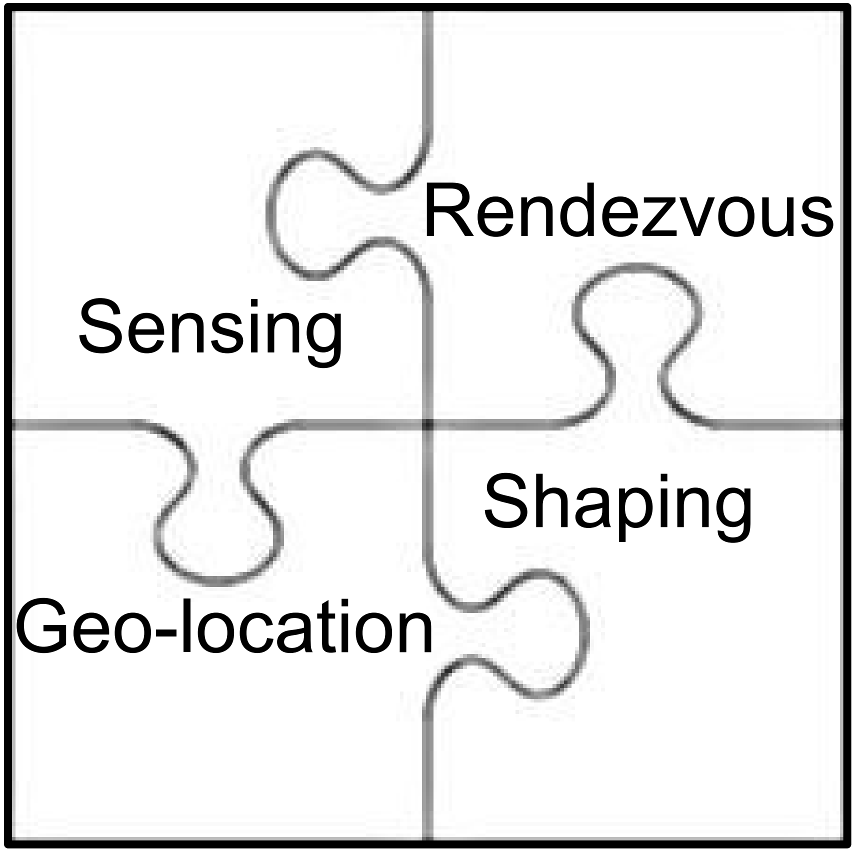
- Evaluation with mature transceiver:
  - Spectrum efficiency
  - Packet error rates
  - TTR, Detection, Identification, Frequency Acquisition
  - With and without the USRPs

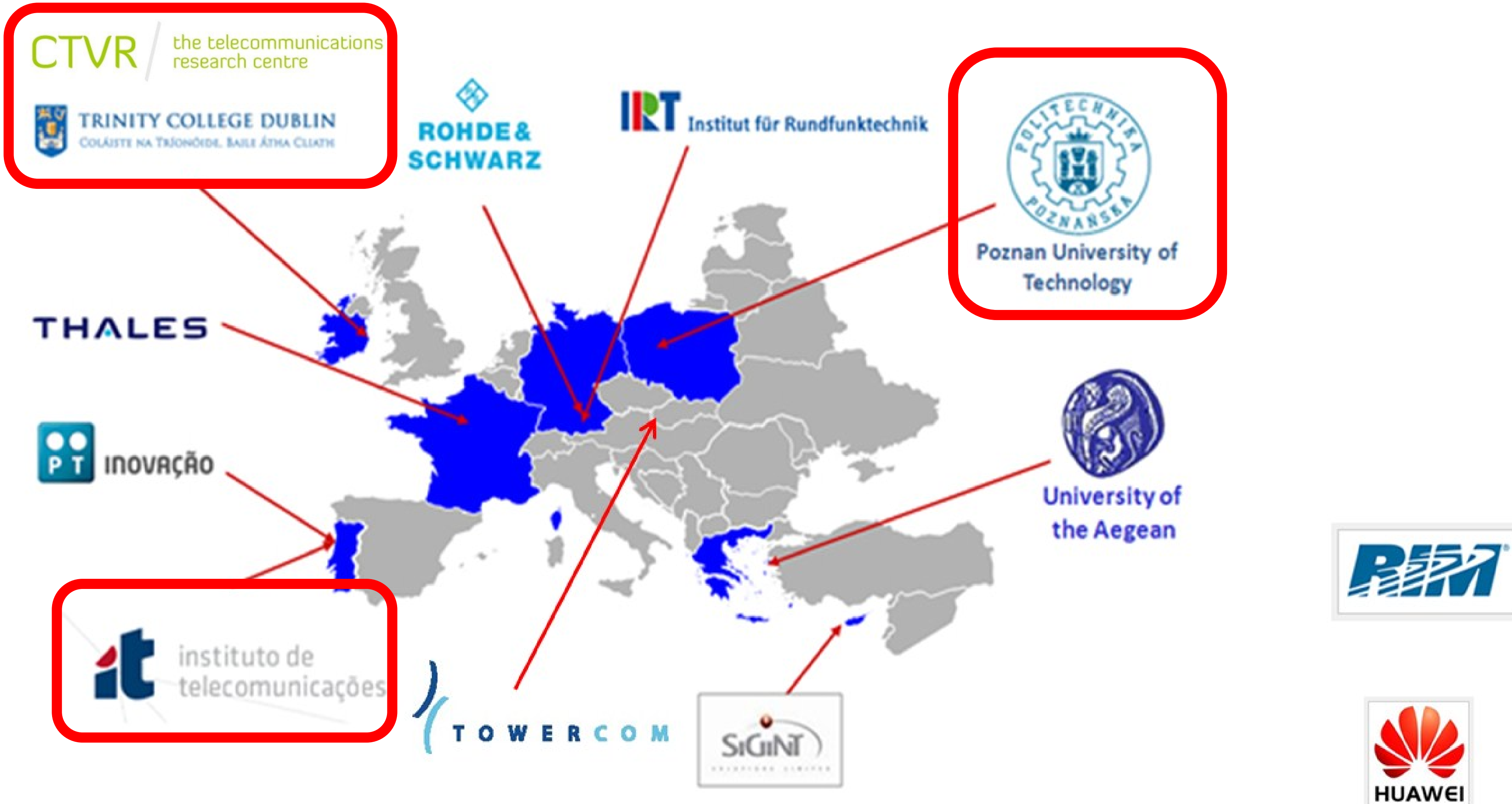




COMPONENTS TO SYSTEM

Experimenting with a system





COGEU

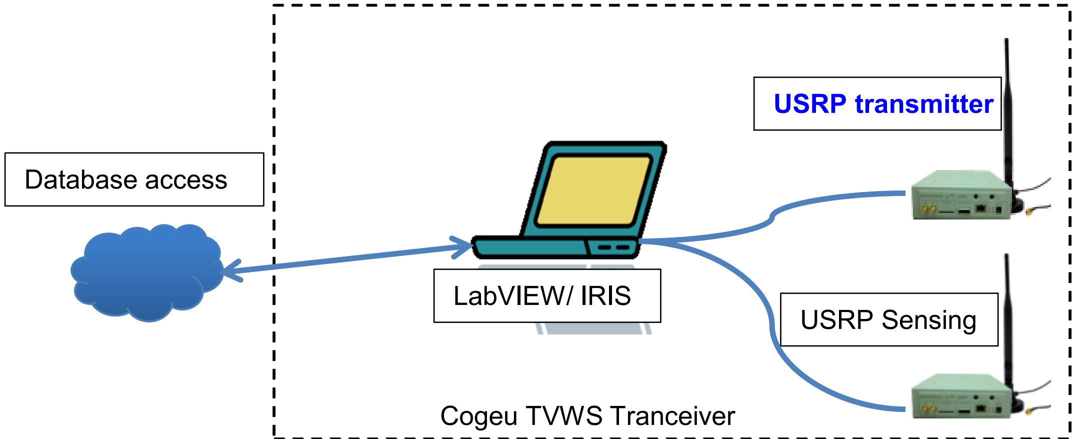
SEVENTH FRAMEWORK PROGRAMME

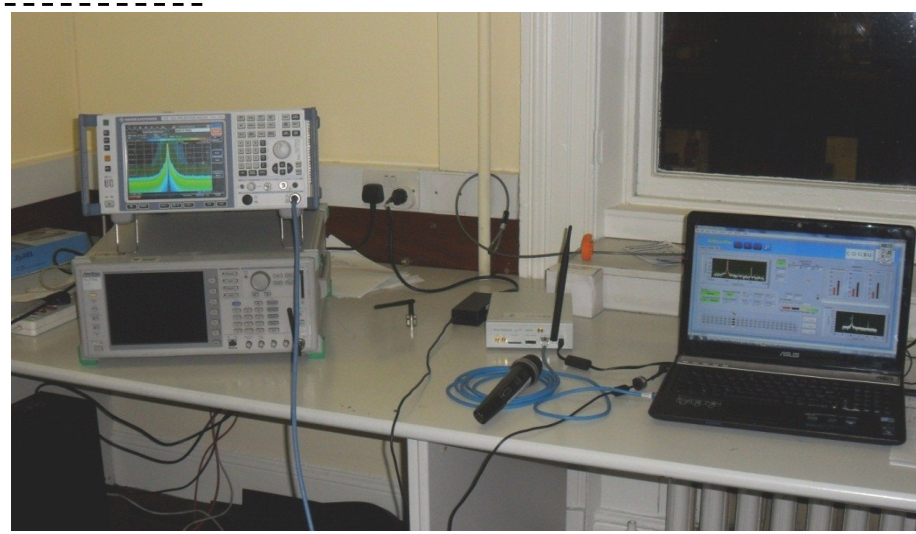
CTVR

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





COGEU

SEVENTH FRAMEWORK PROGRAMME

CTVR

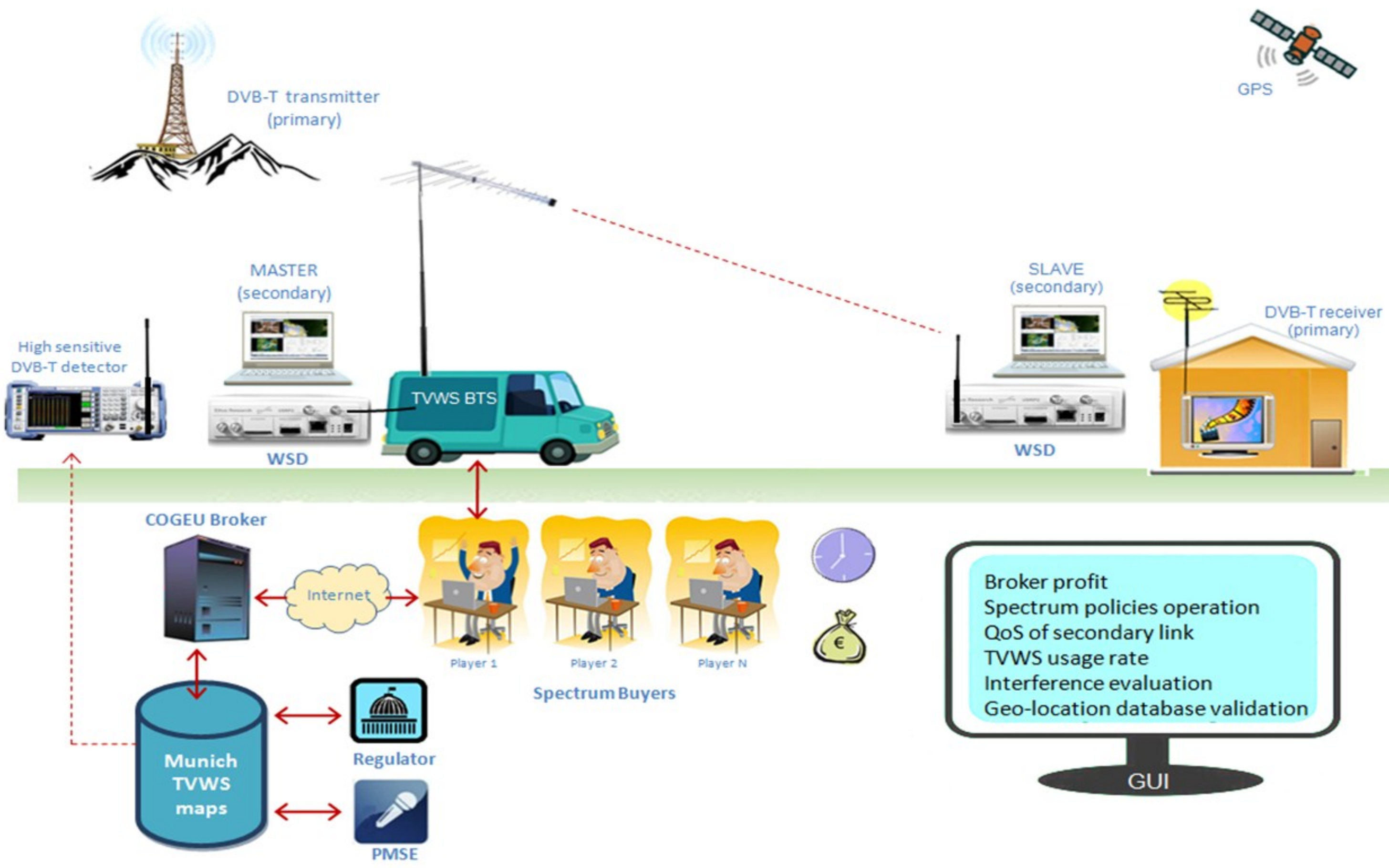
What did we learn ?

- 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



COGEU

SEVENTH FRAMEWORK PROGRAMME

CTVR

Aalborg

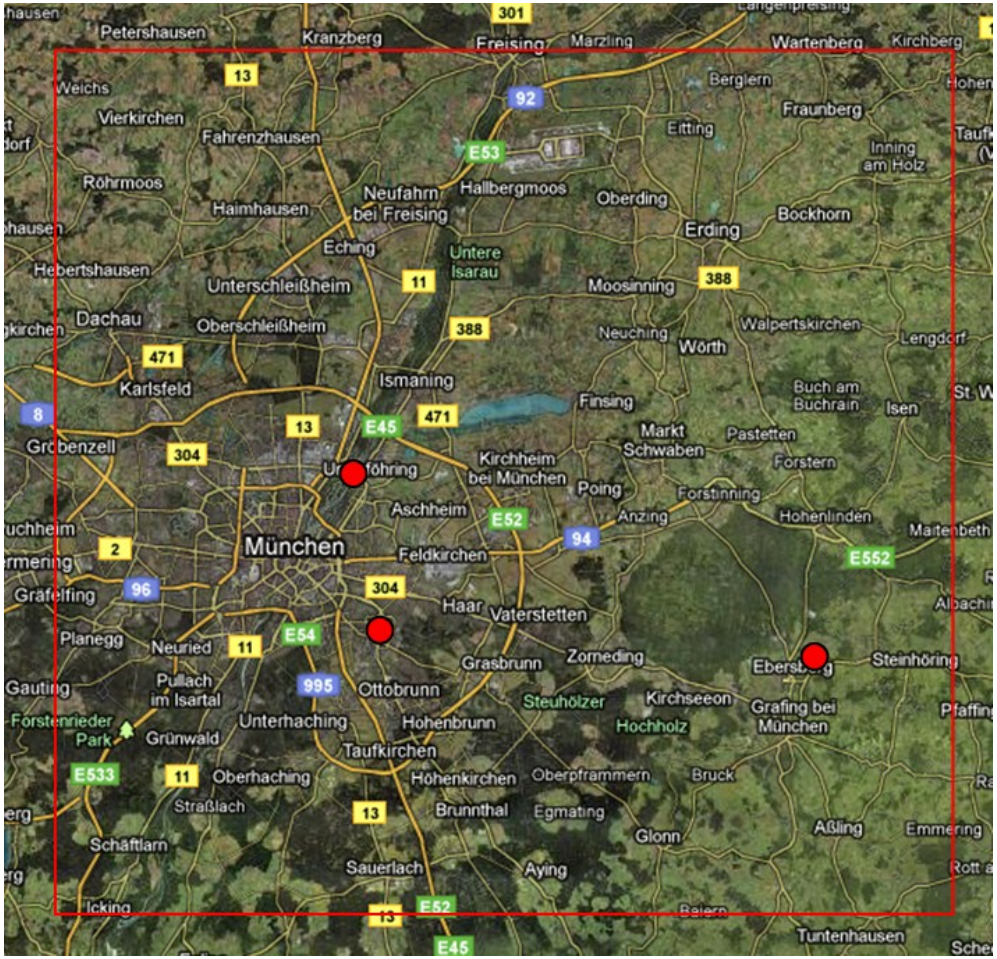
Validation sites

COGEU

SEVENTH FRAMEWORK PROGRAMME

CTVR

Munich



C O G EU

SEVENTH FRAMEWORK PROGRAMME

CTVR

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 COGEU rural broadband scenario.

FIRE

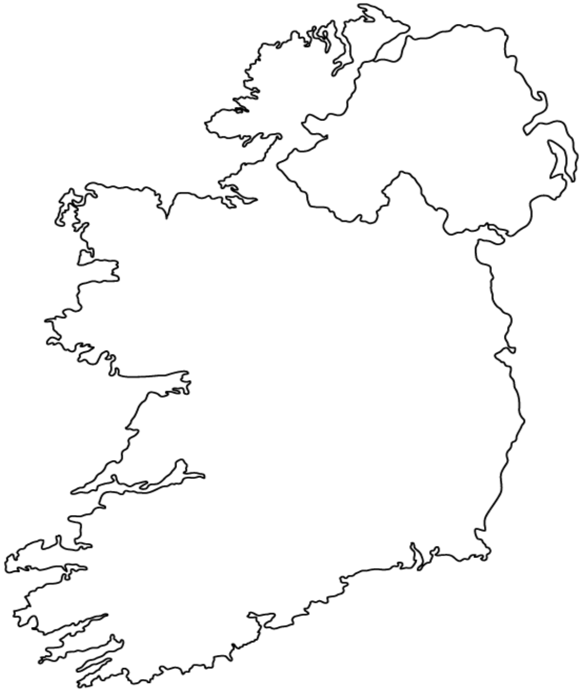
- What is a good experiment?
- How an experiment can be unambiguously defined?
- What output do we expect from an experiment?
- **How do we control the wireless environment?**

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



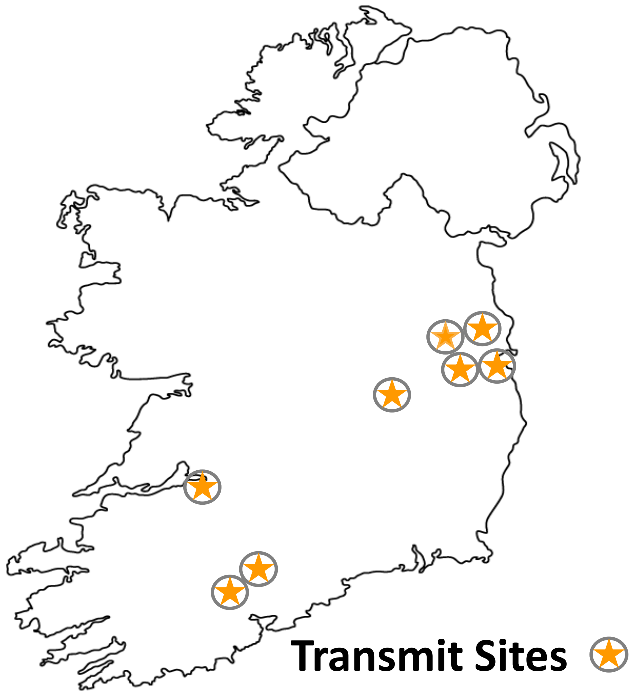
www.testandtrial.ie
www.comreg.ie

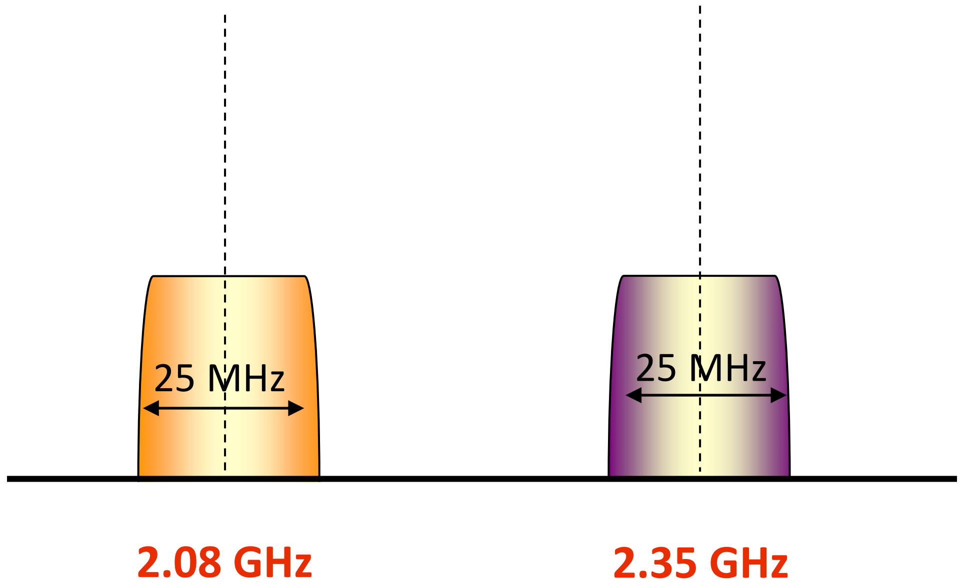
COGEU

SEVENTH FRAMEWORK PROGRAMME

CTVR

CTVR Test & Trial





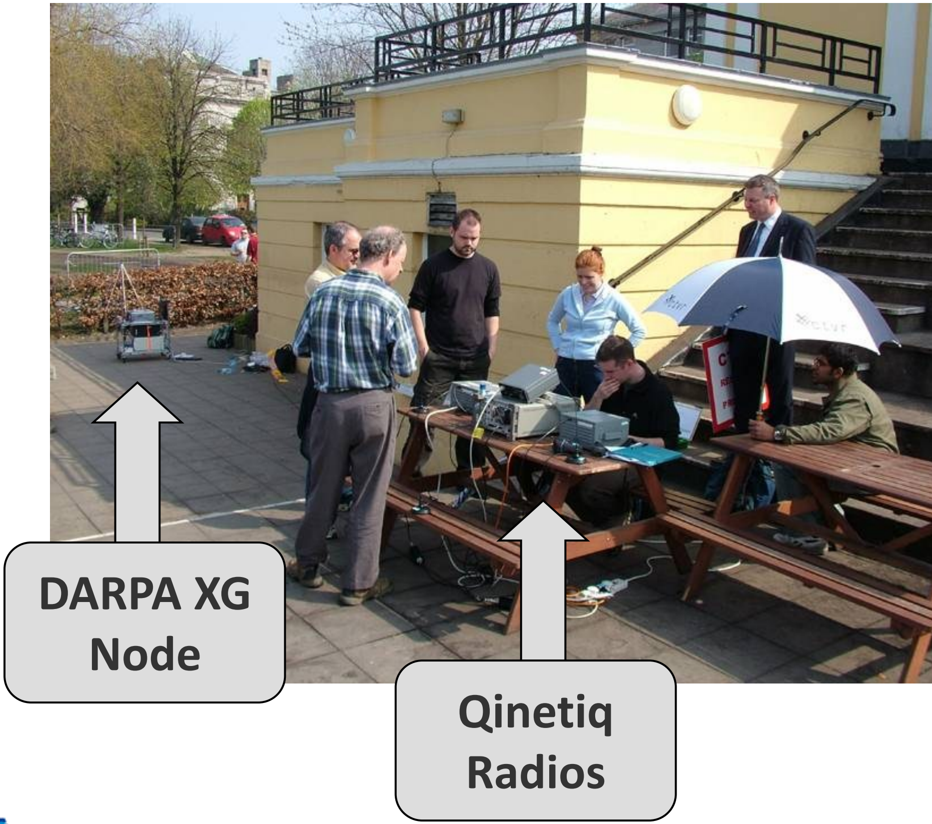
COGEU

SEVENTH FRAMEWORK PROGRAMME

CTVR

IEEE DySPAN 2007 – Dublin

Channel	Centre Freq. (MHz)	Max ERP	BW (MHz)	Mobile
1	231.2250	1 W (0dBW)	1.75	Yes
2	233.0250	1 W (0dBW)	1.75	Yes
3	234.8250	1 W (0dBW)	1.75	Yes
4	236.6250	1 W (0dBW)	1.75	Yes
5	238.4250	1 W (0dBW)	1.75	Yes
6	386.8750	1 W (0dBW)	1.75	Yes
7	396.8750	10 W (10dBW)	1.75	Yes
8	406.9750	1 W (0dBW)	1.75	Yes
9	408.7750	10 W (10dBW)	1.75	Yes
10	436.8750	1 W (0dBW)	1.75	Yes
11	2056.0000	1 W (0dBW)	50.0	No
12	2231.0000	1 W (0dBW)	50.0	No

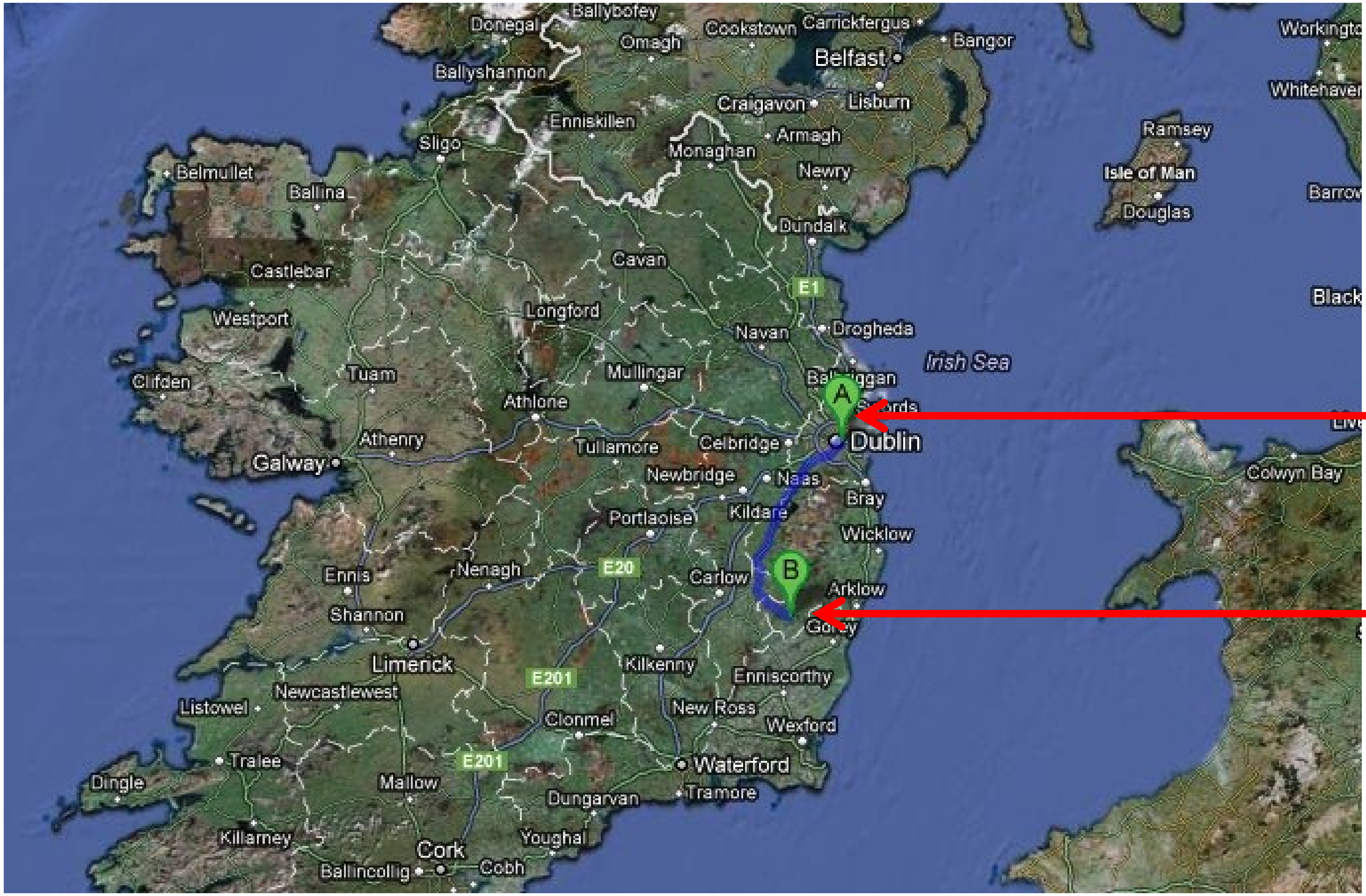


COGEU

SEVENTH FRAMEWORK PROGRAMME

CTVR

Test & Trial



CTVR

NOWHERE
or
90km from
SOMEWHERE

CTVR

Conclusions

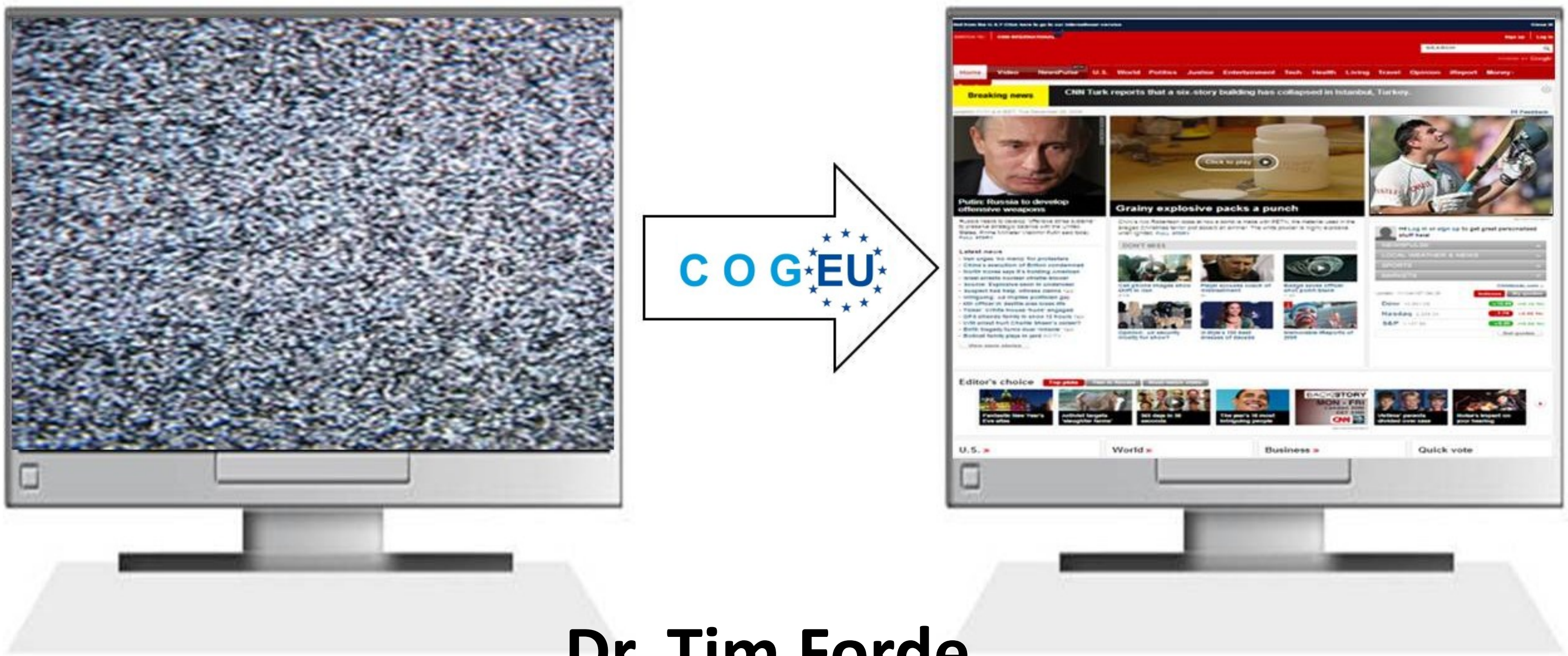
- What is a good experiment?
- How an experiment can be unambiguously defined?
- What output do we expect from an experiment?
- How do we control the wireless environment?

COGEU

SEVENTH FRAMEWORK PROGRAMME

CTVR

Questions



Dr. Tim Forde
fordeti@tcd.ie