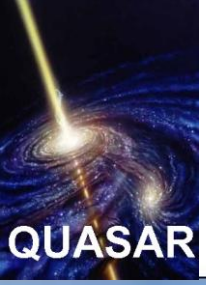

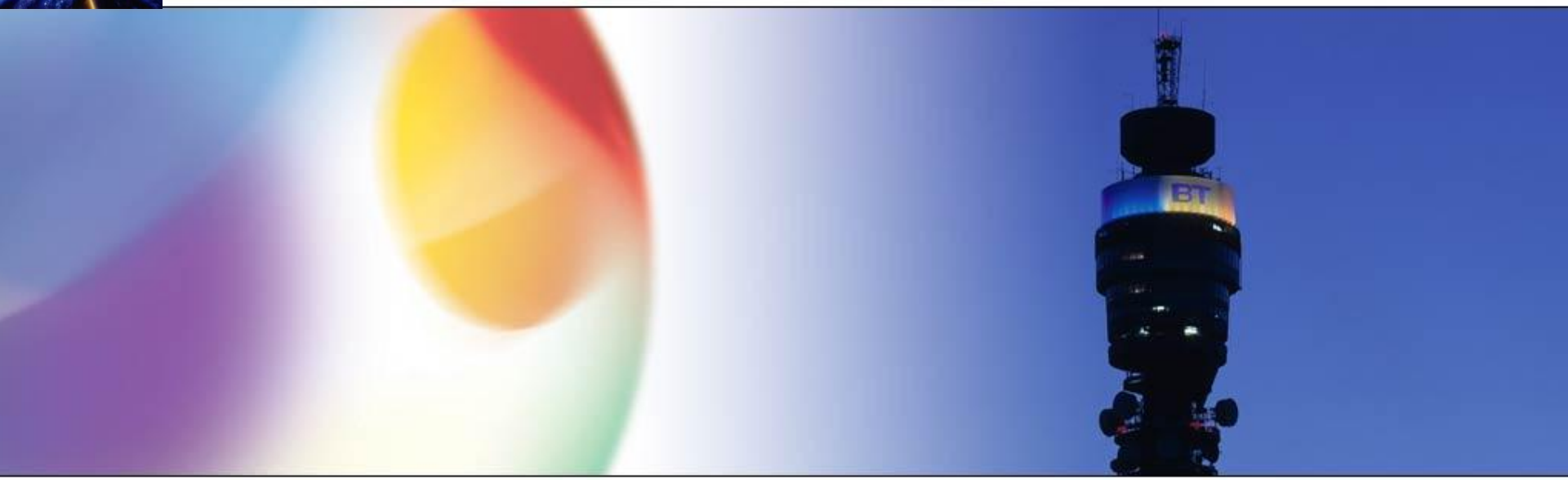

Cognitive Radio for Secondary Spectrum Access

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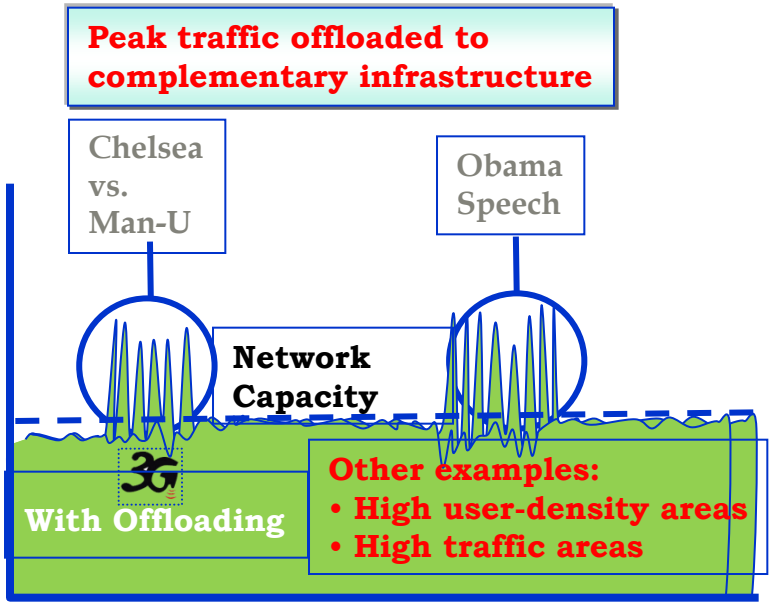
Content

- What we do, why we are interested in secondary access
- EU collaborative projects: QUASAR, QOSMOS
- BT's Research on cognitive access to TV White Spaces
- QUASAR's initial research results (6 months)
  - Sharing models and scenarios
  - Methodology for assessing secondary usage opportunity
  - Interference tolerance of (legacy) primary systems
- Conclusions

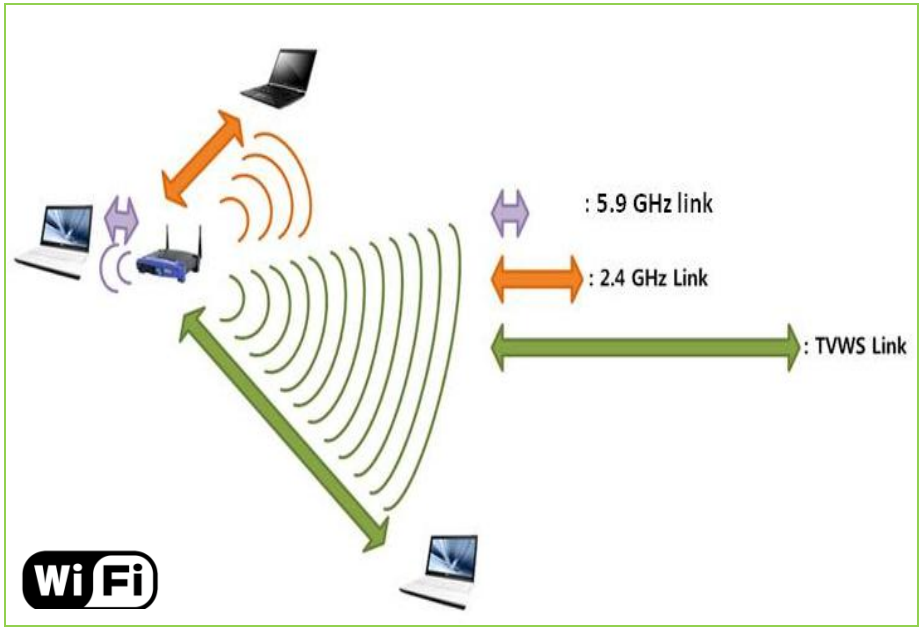
Who we are and what we do

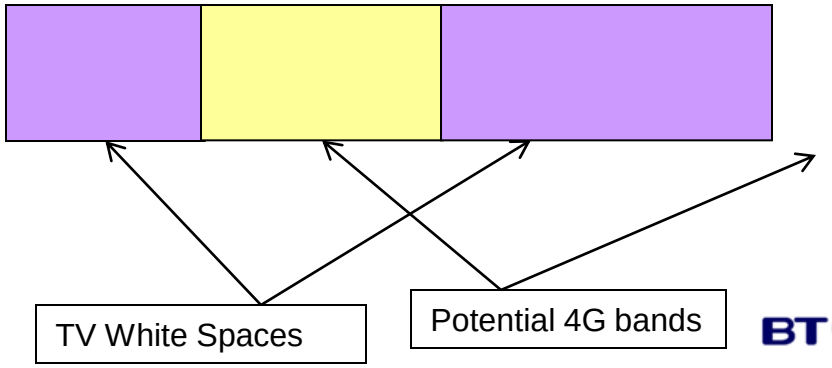
- One of the world's leading communication services companies, providing services in 170 countries
- Mainly a fixed-line operator. However
- Largest supplier of managed backhaul services to UK's cellular operators
- Mobile voice and data supplier to both business and consumer segments through MVNO agreements
- Largest WiFi hotspot estate in the UK (~150K) and one of the largest WiFi community networks in the world: BT FON, over 1M members
- WiFi offload for cellular operators
- Communication infrastructure for UK's smart grids (just announced)



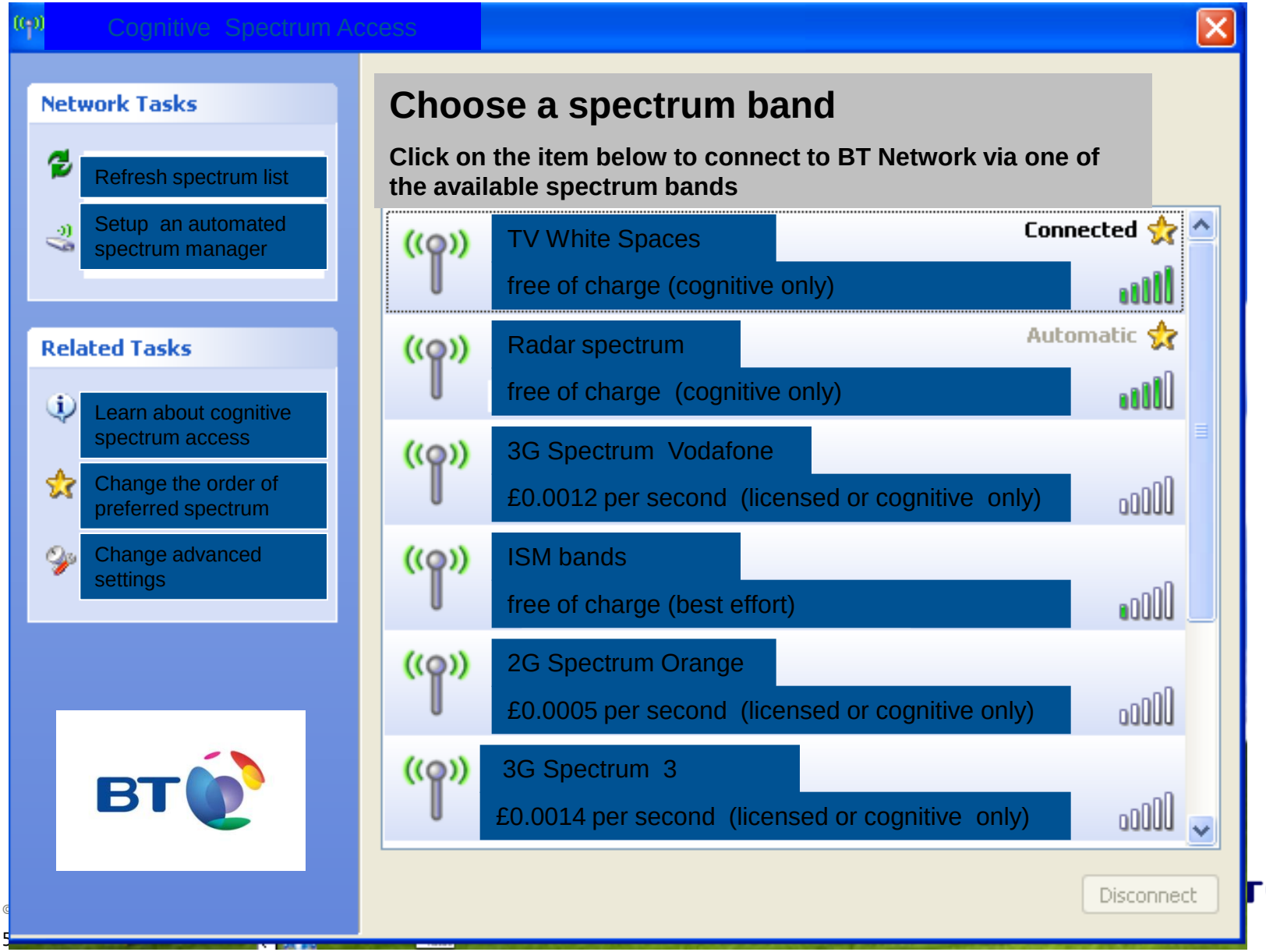
Why is TVWS spectrum interesting to BT?

- TVWS is licence-exempt spectrum in the very desirable UHF bands (UK, Europe)
- On average a significant ~100-150 MHz TVWS is available in the UK
- TVWS can delivers significantly longer range and better penetration through walls and buildings compared to 2.4 GHz and 5 GHz ISM bands
- It could work as **super-WiFi** or for congestion relief, but may also enable entirely new services for BT's customers
- TVWS could be attractive to some cellular operators, as a licence-exempt addition to their licensed 4G spectrum, e.g. for data offload and wireless backhaul





Going beyond TVWS, a spectrum portfolio



European collaborations

- **QoSMOS – Integrated Project (IP)**
  - 36 months started 1/1/10.
  - 16 European partners + Japan,
  - BT is coordinating partner
  - Addressing QoS, mobility, plus spectrum portfolio management and proof-of-concept demonstrations

- **QUASAR – Specific Targeted Research Project (STREP)**
  - 30 months started 1/1/10
  - 11 European partners +Korea
    4 Regulators (UK,GR, SWE, FI)
  - BT leads WP1 (use cases, regulatory & business)
  - Addressing primary user's interference limits, multiple secondary users, primary-secondary collaboration, regulatory models and requirements, business models, use of utility functions, from spectrum holes to spectrum opportunities

•Also UK-India and UK-China collaborations on CR/4G
•Open to new ones

At A Glance: QUASAR

Quantitative Assessment of Secondary Spectrum Access

Project Coordinator
Jens Zander
Wireless@KTH,
Royal Institute of Technology (KTH)
Tel: +46 8 790 9351
Fax:+46 8 790 9370
Email:jenz@kth.se
Project website:www.quasarspectrum.eu

Partners: KTH (SE), Ericsson AB (SE), RWTH Aachen University (DE), TKK (FI), Yonsei University (Rep. of Korea), BT PLC (UK), BNetzA (DE), Ss Cyril & Methodius University (Macedonia), PTS (SE), Ofcom (UK), FICORA (FI)

Duration: *January 2010 – June 2012*
Funding scheme: *STREP*
Total Cost: *€5.049m*
EC Contribution: *€2.996m*

Contract Number: INFSO-ICT-*248303*

BT’s Research on Cognitive Access to TVWS

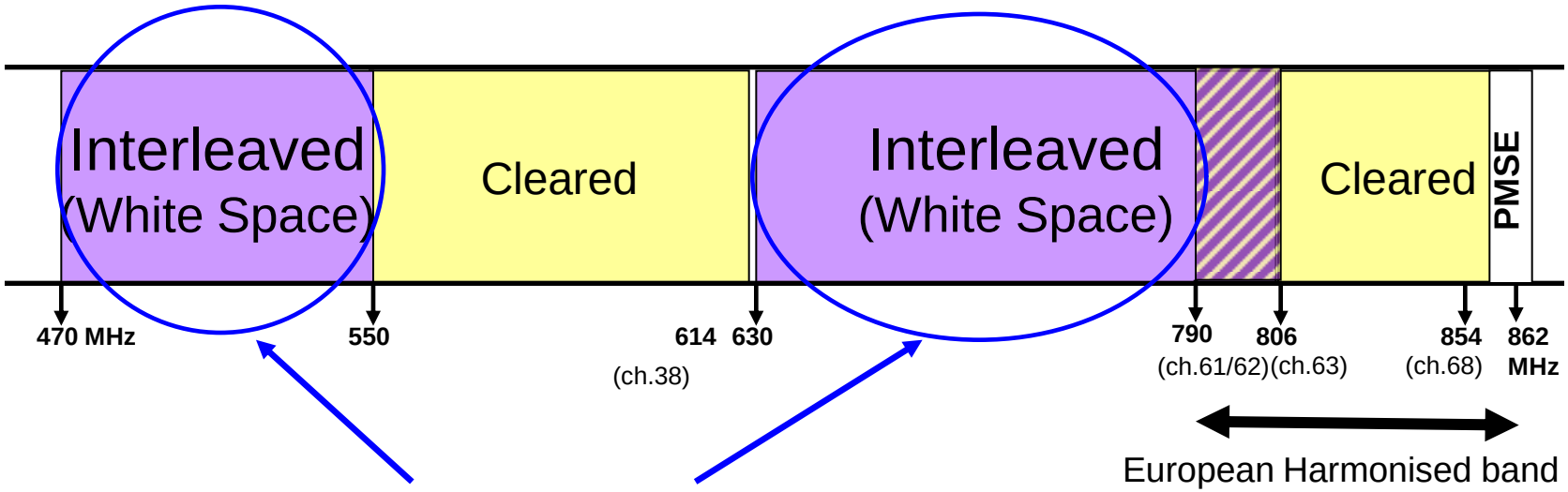
Industry standards

- IEEE 802.22
  - PHY AND MAC for Rural broadband in TVWS. Final draft expected 2010
- IEEE 802.18
  - Co-existence in TVWS
- IEEE 802.11af
  - PHY and MAC for WiFi operation in TVWS
- CogNeA/ECMA392*
  - PHY and MAC , mainly for home network applications in TVWS (HDTV streaming), 1st draft published in 2009
- WiFi Alliance*
  - TV White Space Marketing task force formed (July 2010). Focus is on creating a certification program for enhanced WiFi services TVWS
- ETSI RSS*
  - European standardisation of reconfigurable radio systems based on CR and SDR technologies., support regulation

* BT participating

Ecosystem/industry partners in TVWS

How much TV White Space is there in the UK?



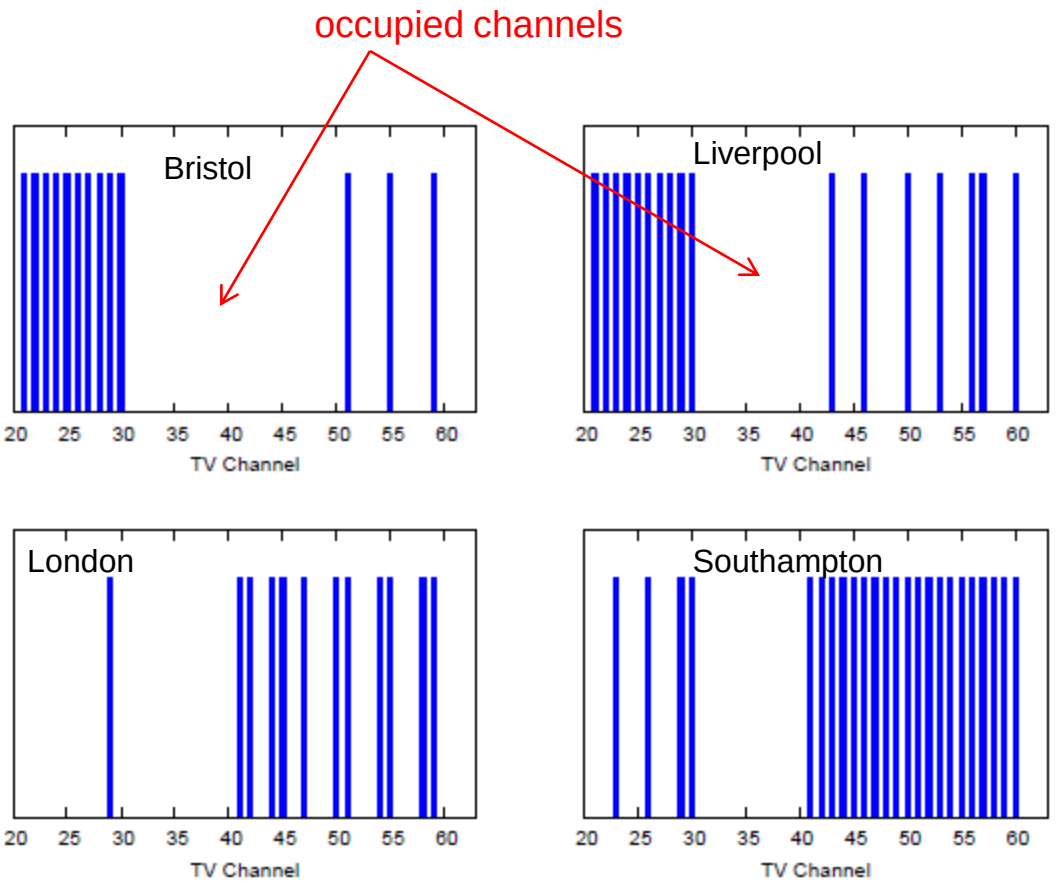
European Harmonised band (72 MHz wide) for mobile 790 – 862 MHz (ch. 61-69)

- Licensed use by broadcast applications (national/local TV); Programme Making & Special Events (PMSE); Wireless microphones.
- Licensed-exempt secondary use by devices equipped with cognitive techniques/look-up databases
- 256 MHz in total, all in the UHF bands, 8 MHz channels (unlike in the USA)
- **However, availability varies greatly with location and power !**

Example TVWS availability

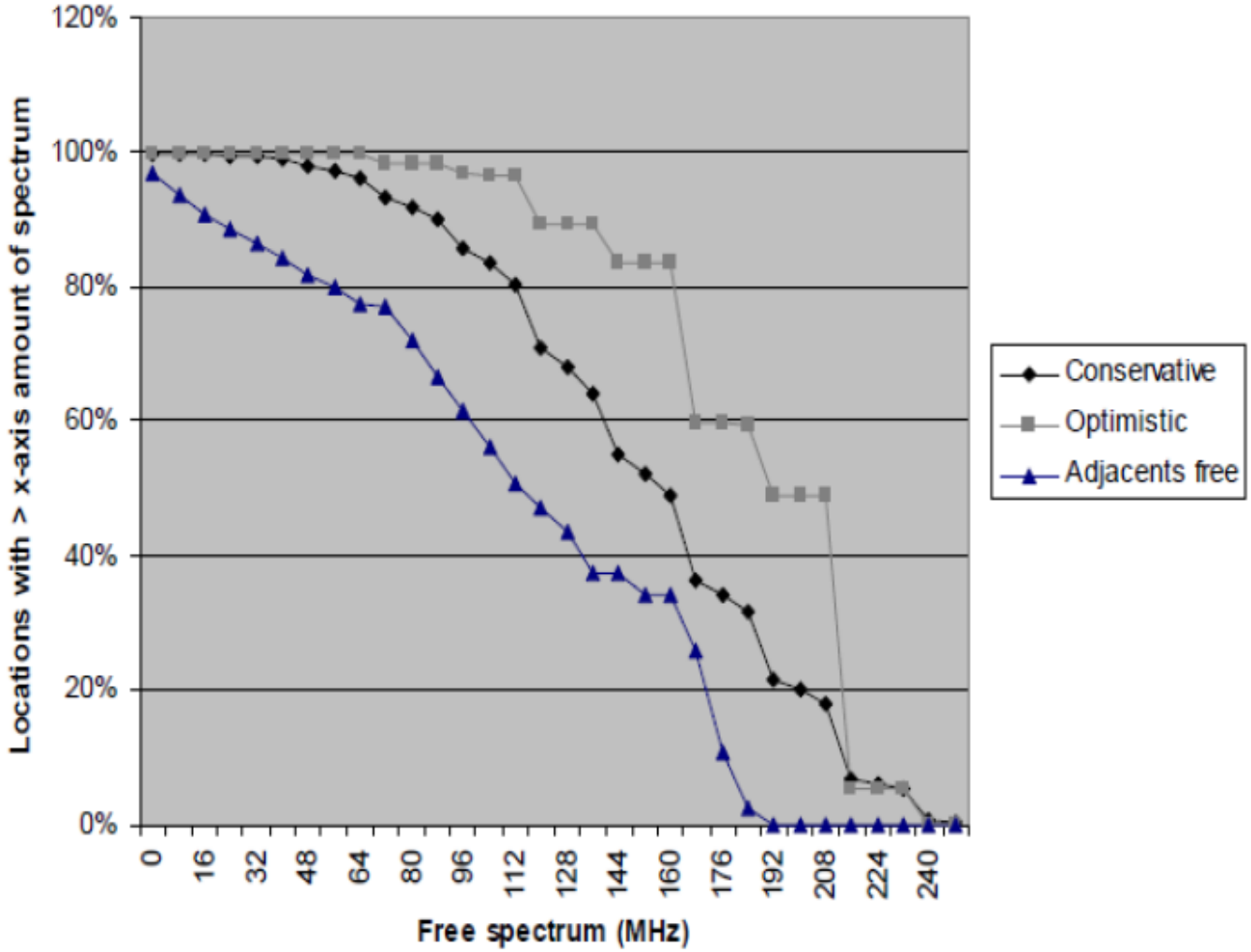
Calculation method

- Used publicly available DTT coverage maps
- Verified with own coverage calculations for selected transmitters
- Channel m available at location x for a given CR transmit power P if D/U ration is below threshold at the edge of coverage area
- Low transmit power approximation
- **On average ~150 MHz available at any UK locations**
- **Full-blown calculations using STRM v2 terrain elevation data + DTT propagation models in progress**



Source: Nekovee, ICC 2009

Ofcom's published estimates of TVWS



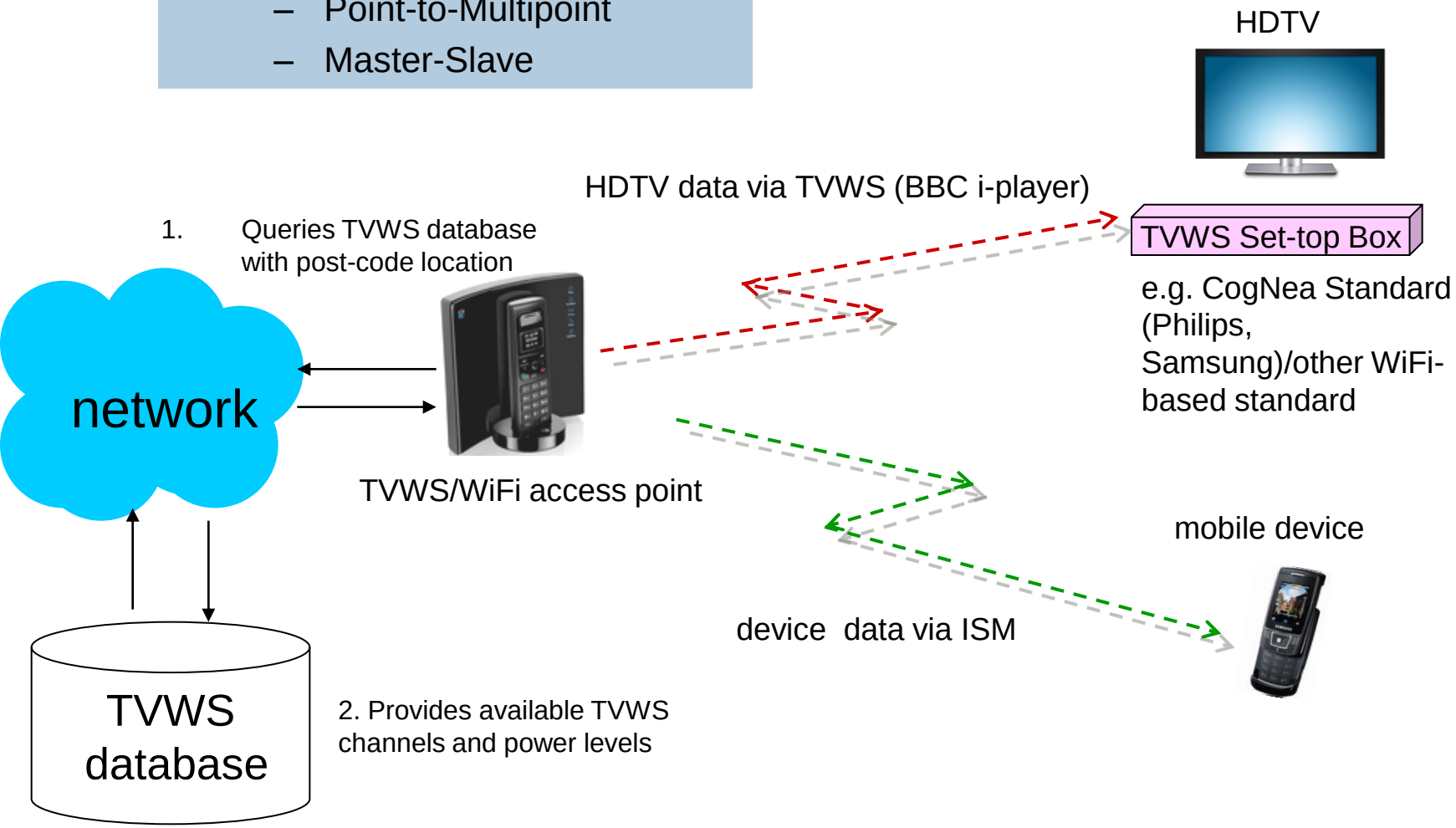
Source Arqiva study, commissioned by Ofcom, July 2009

Use case 1: Multimedia distribution in homes

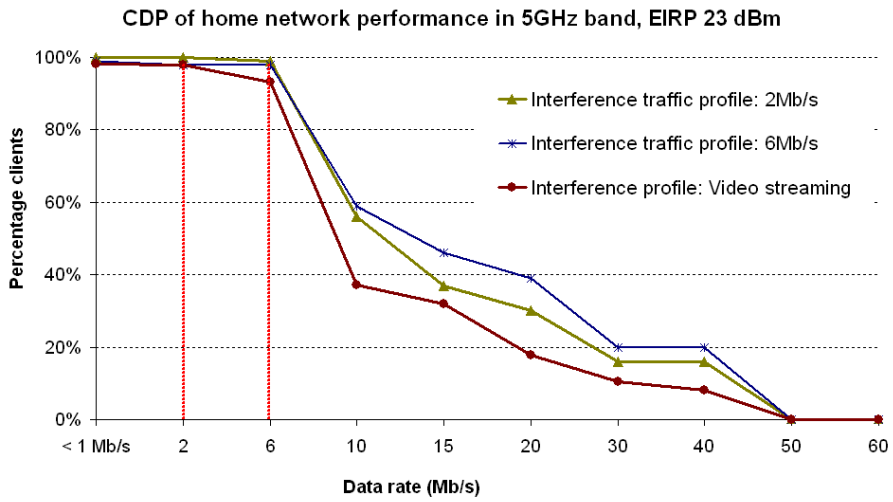
- There is a growing demand for wireless distribution of multimedia content around the home:
  - (HD)TV and “catch-up” (HD)TV
  - Video On Demand
  - BT Vision
- Future scenarios may involve multiple streams of content being distributed simultaneously around the home
- Current license-exempt options are the 2.4 GHz and the 5 GHz bands.
- In dense urban areas the 2.4 GHz band suffers from congestion (due to a combination of interference and WiFi’s inefficiencies)
- The 5 GHz band is not congested but signals do not penetrate well through walls and have a shorter range.
- The TVWS spectrum offers both additional capacity and extended range.

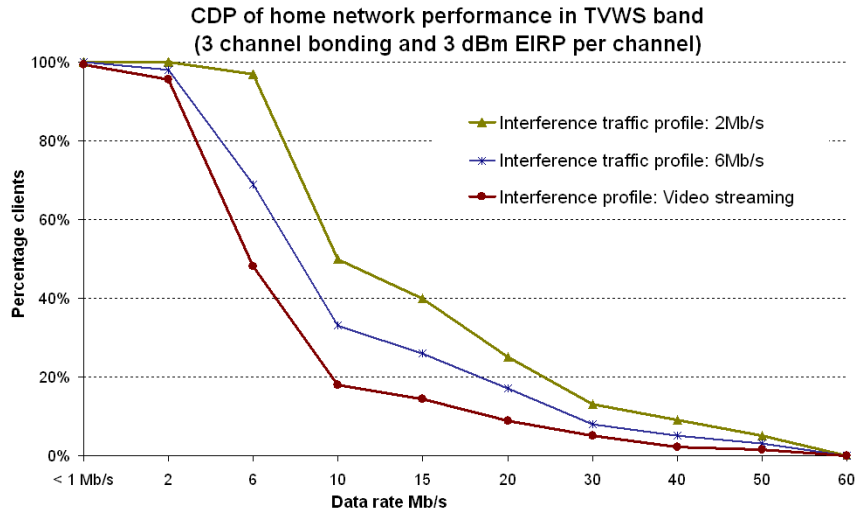
Use case 1: Architecture

- Architecture
  - Point-to-Multipoint
  - Master-Slave



Use case1: System performance with interference



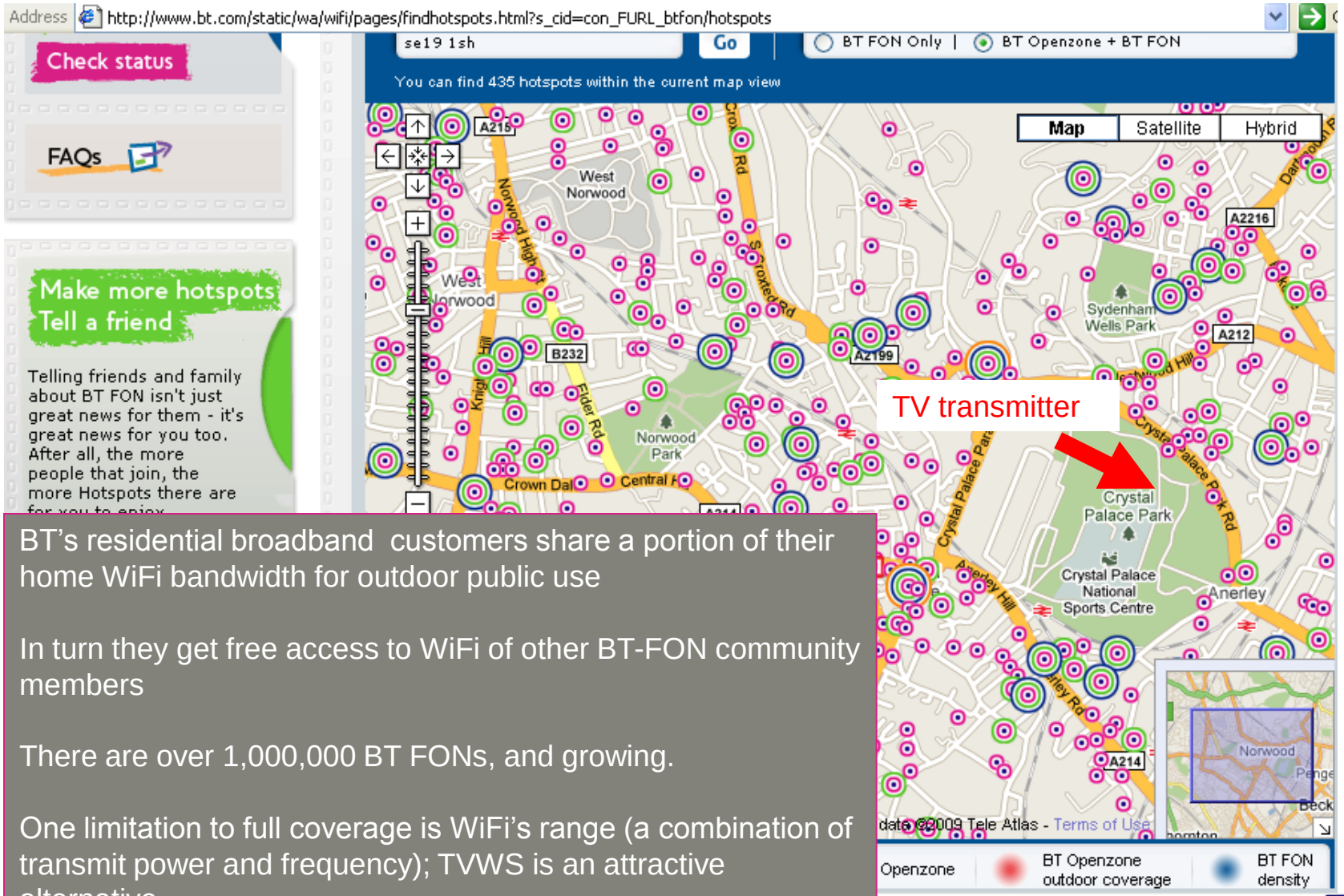


- 3 interference traffic levels 2 Mbps, 6 Mbps, Video
- Service area – 1sq km in London, household density 5K
- access point density – 40%,
- 12 m service area
- TVWS: 3x 8 MHz channels bonded
- transmit power 3 dBm (per channel),
- No MIMO (2x2 for WiFi)

- TVWS for home networks is interference limited if used alone!
- Non-contagious channel bonding is very challenging (NC-OFDM, filter banks, ..)

Source: Kawade and Nekovee, IEEE DySPAN 2010

Use case 2: Broadband “from the inside-out”



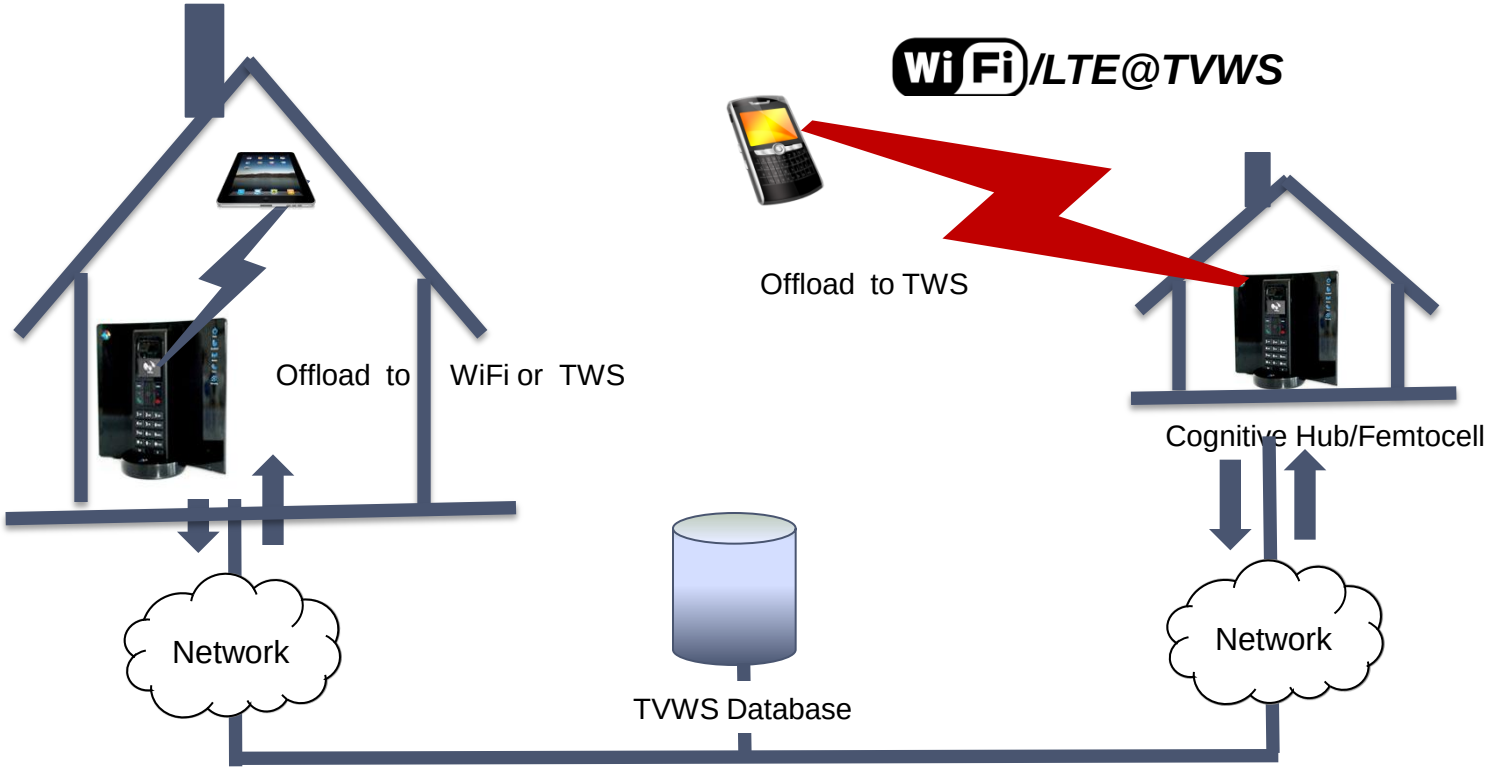
BT’s residential broadband customers share a portion of their home WiFi bandwidth for outdoor public use

In turn they get free access to WiFi of other BT-FON community members

There are over 1,000,000 BT FONs, and growing.

One limitation to full coverage is WiFi’s range (a combination of transmit power and frequency); TVWS is an attractive alternative.

Use case 2: architecture



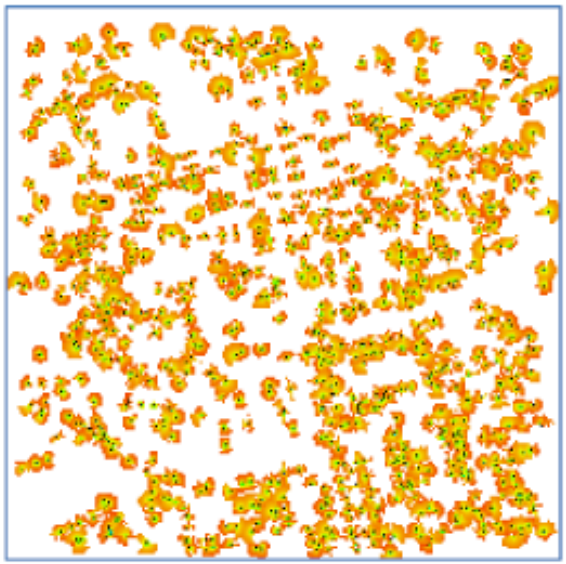
- A spectrum database is used to avoid harmful interference to incumbents and assign TVWS channels (and power levels) to access points
- Master-slave topology, most functionalities in hubs/femtocells,

Use case 2: coverage study

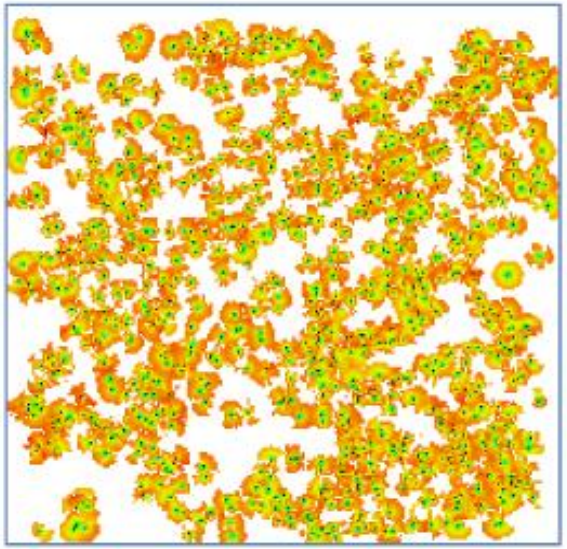
Area – 1sq km in London (Bayswater), household density 5K

Access point density – 0.5%, 2%, 5%, 10%, 20%, 30%, 40%

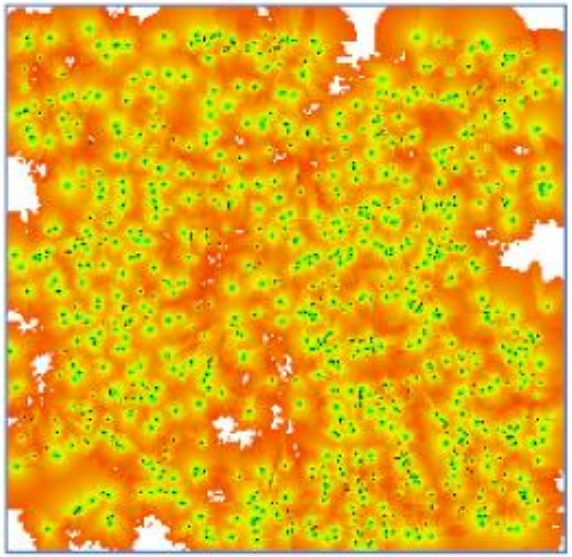
Spectral bands considered: TVWS, 2.4GHz and 5GHz



(a) 5GHz



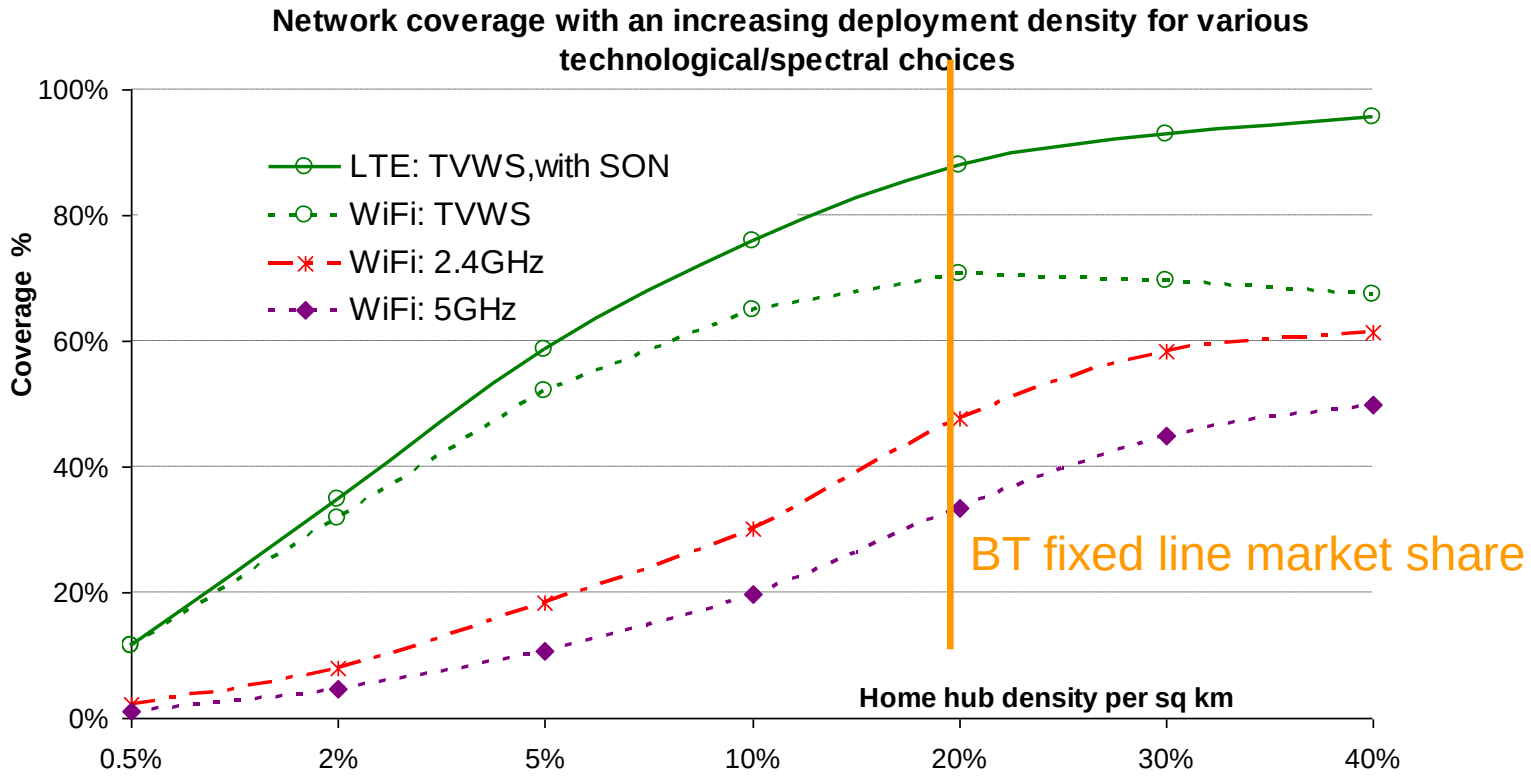
(b) 2.4GHz



(c) TVWS

TVWS band provides coverage similar to a mobile broadband network – with a 20% deployment density

Use case 2: Network coverage with increasing deployment density



TVWS: 90% coverage possible with a 20% density, LTE-SON features help

WiFi in 2.4GHz: coverage limited to 60% due to interference effects

WiFi in 5GHz: coverage limited to 50% due to higher attenuation losses

Source: Kawade and Nekovee, Radioelectronica, 2010

Use case 3: Rural broadband

• 2 million UK households (mainly in rural areas) have inadequate access to broadband (<2Mb/s)

• Fixed-line broadband provision to these communities is economically not viable for telecom operators .

• One options is wireless broadband provision using a combination of WiFi@5GHz (point-to-point) and WiFi@2.4GHz bands (point-to-multipoint)

• The build-out cost of a WiFi-based network is high due to unfavourable propagation characteristics in the ISM bands, and UK's regulatory limits on WiFi transmit power (100 mW)

•The study looks at providing BWA in TVWS from BT's exchanges

•The aim of the study is to identify UK locations where the TVWS solution is feasible, i.e., there is both sufficient density of households in the not-spot area and sufficient TVWS bandwidth to support 2 Mbps

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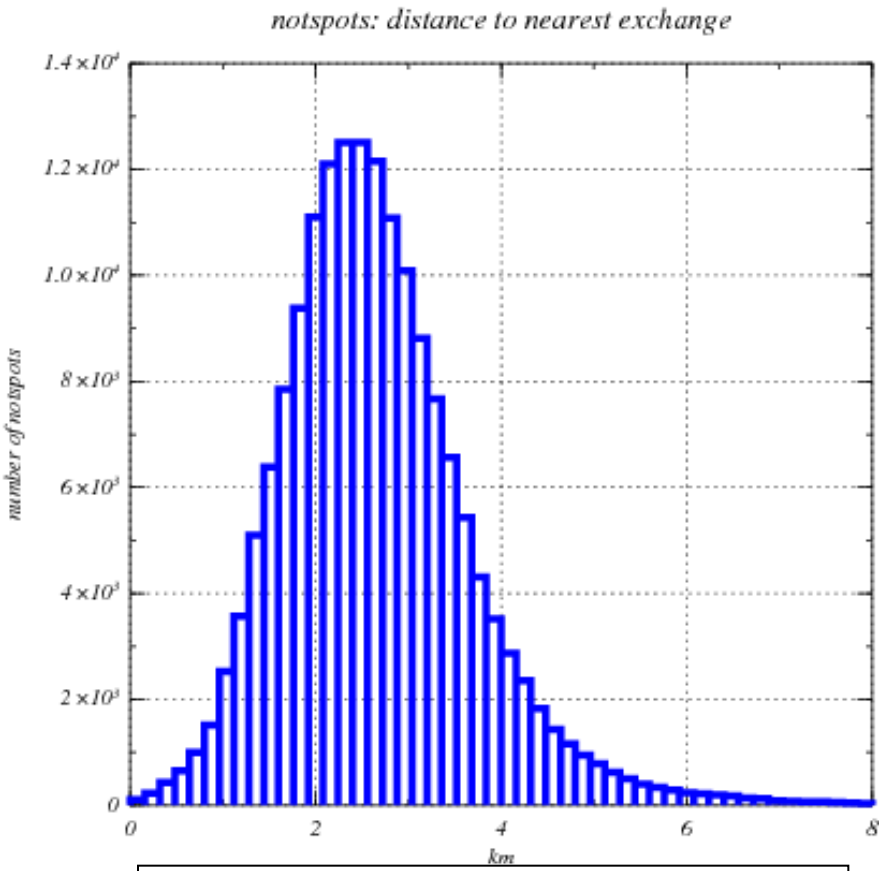
Use case 3: modeling study

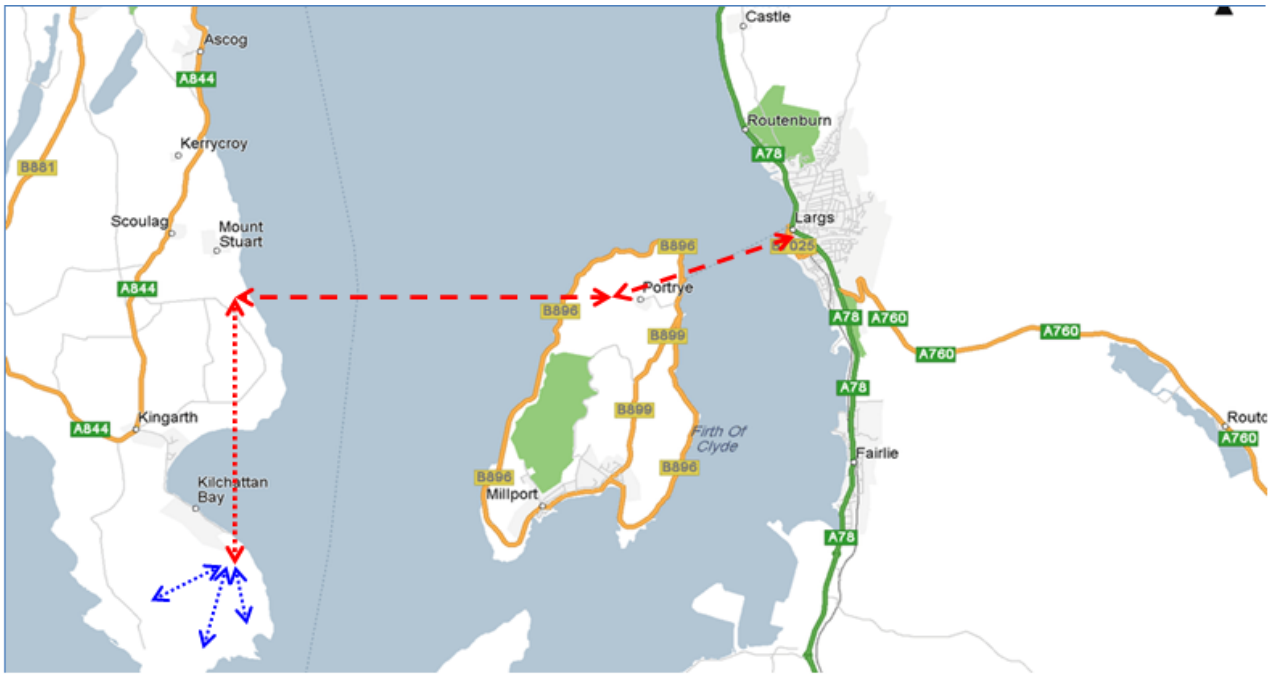
- **Not-spots:**
  UK postcodes that get less than 2Mbps fixed broadband.
- Internal BT data of ~3.5 million not-spots post codes and 5500 BT exchanges was used for the analysis
- Distance from each not-spot to closest exchange is calculated
- The average distance between the not-spots and nearest BT exchange is about 3km. The maximum distance is less than 6 km.
- The average TVWS bandwidth per not-spot is ~100 MHz



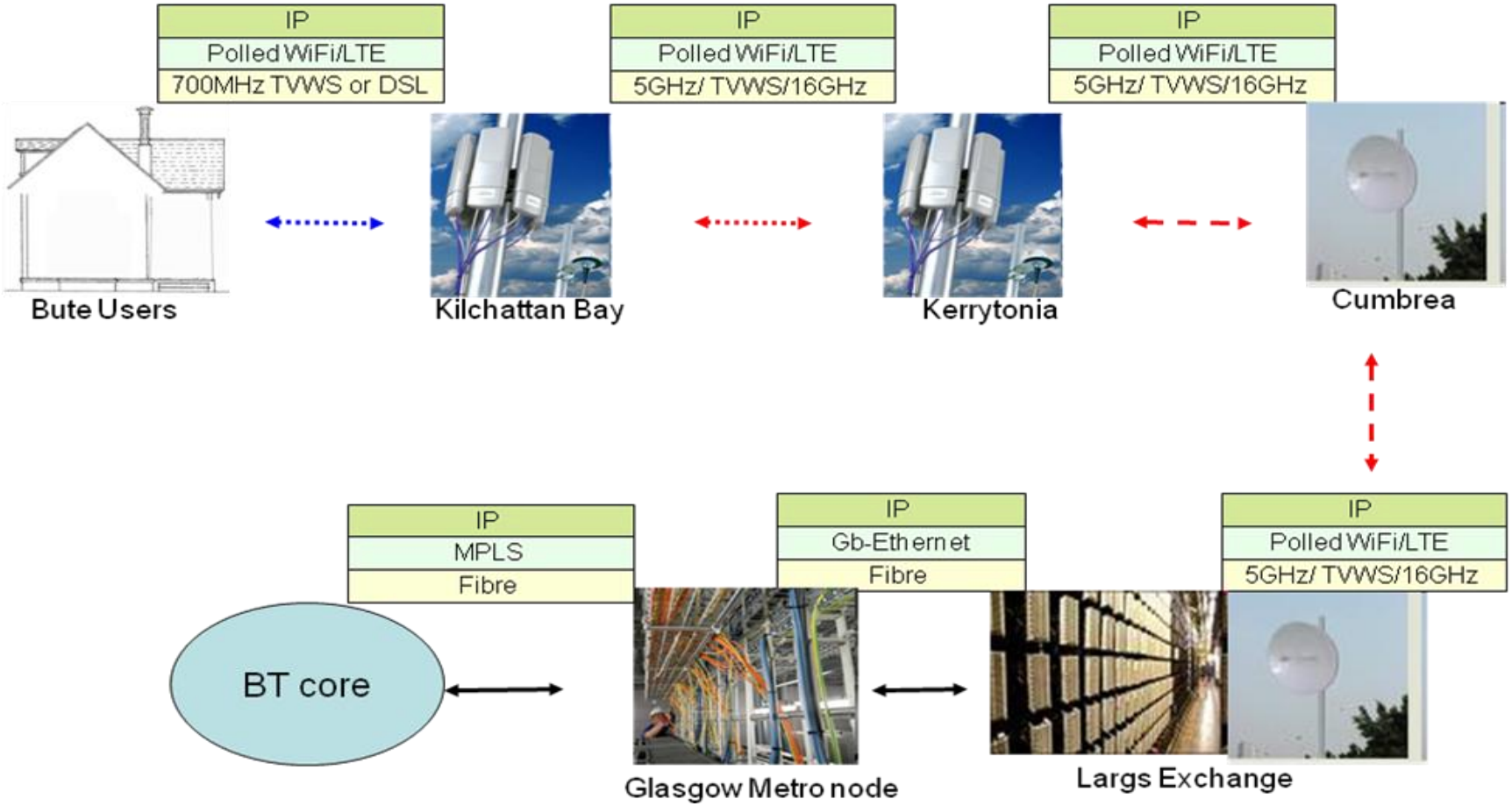
Histogram of distances between not-spots and the closets BT exchange

Use case 3: Trials

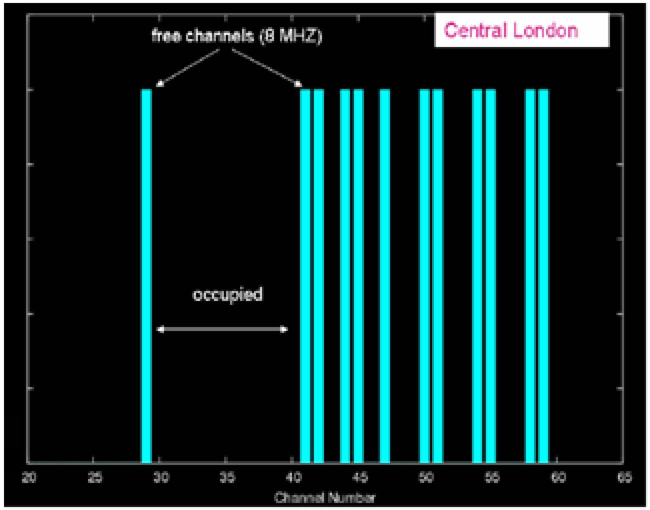
- Aim of the trial is to demonstrate/test the feasibility of wireless broadband to UK rural communities in TV White Spaces
- Trial location is the Isle of Bute in Scotland
- Partners are BT, BBC, University of Strathclyde, Steepest Ascent and Brew Your Own



Physical layer network layout



Challenges of TVWS/CR Networks



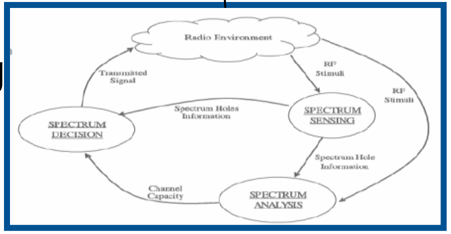
•Real-life deployment scenarios involve collections of cognitive radios (user devices, base stations) competing for spectrum access
•Most research has focused on single devices

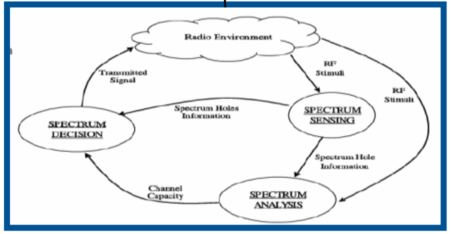
Implications for MAC and network layers

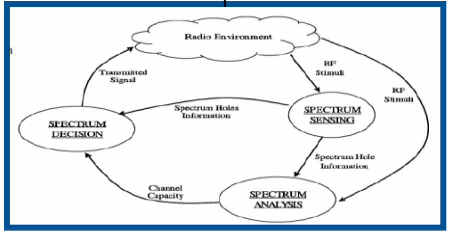
– New spectrum access rules (etiquettes) are required for fare and efficient sharing of secondary spectrum (micro-economics?)

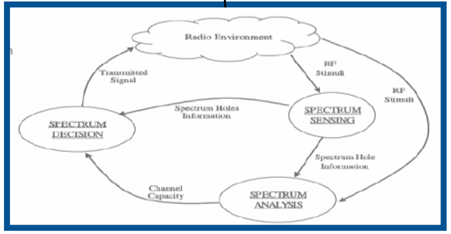
– Aggregate interference to primary systems need to be estimated and controlled (distributed vs. centralised)

– Sensing under secondary emissions









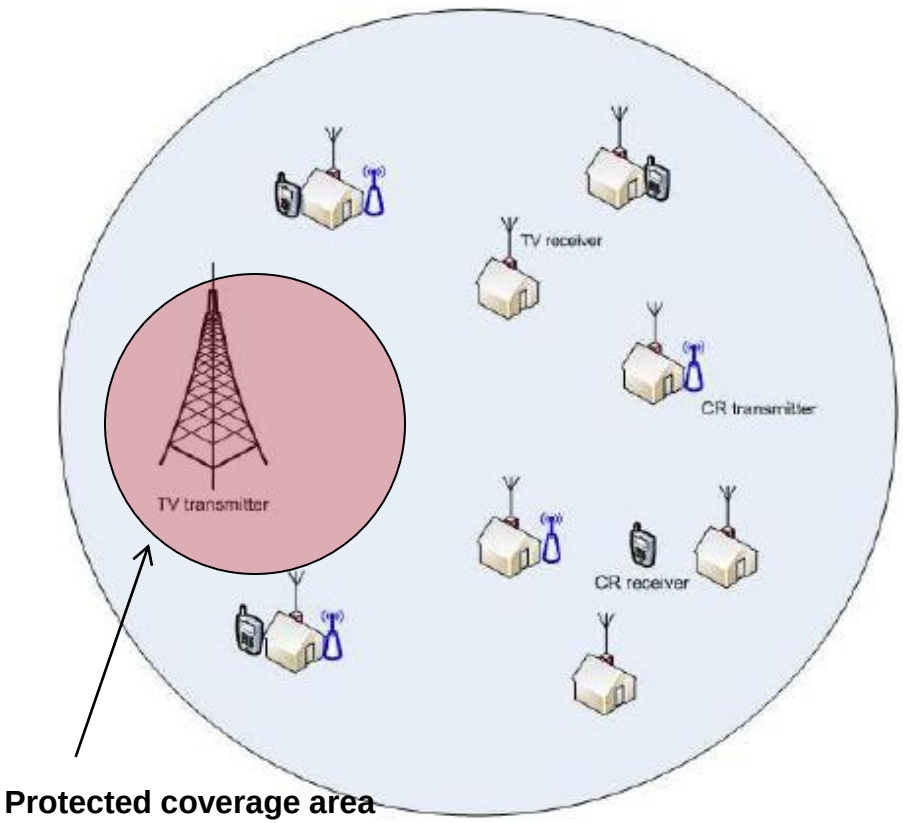
BT

Aggregate interference control

While transmission from a single cognitive device may not cause any harmful interference to primary systems, the aggregate interference maybe harmful and need to be controlled

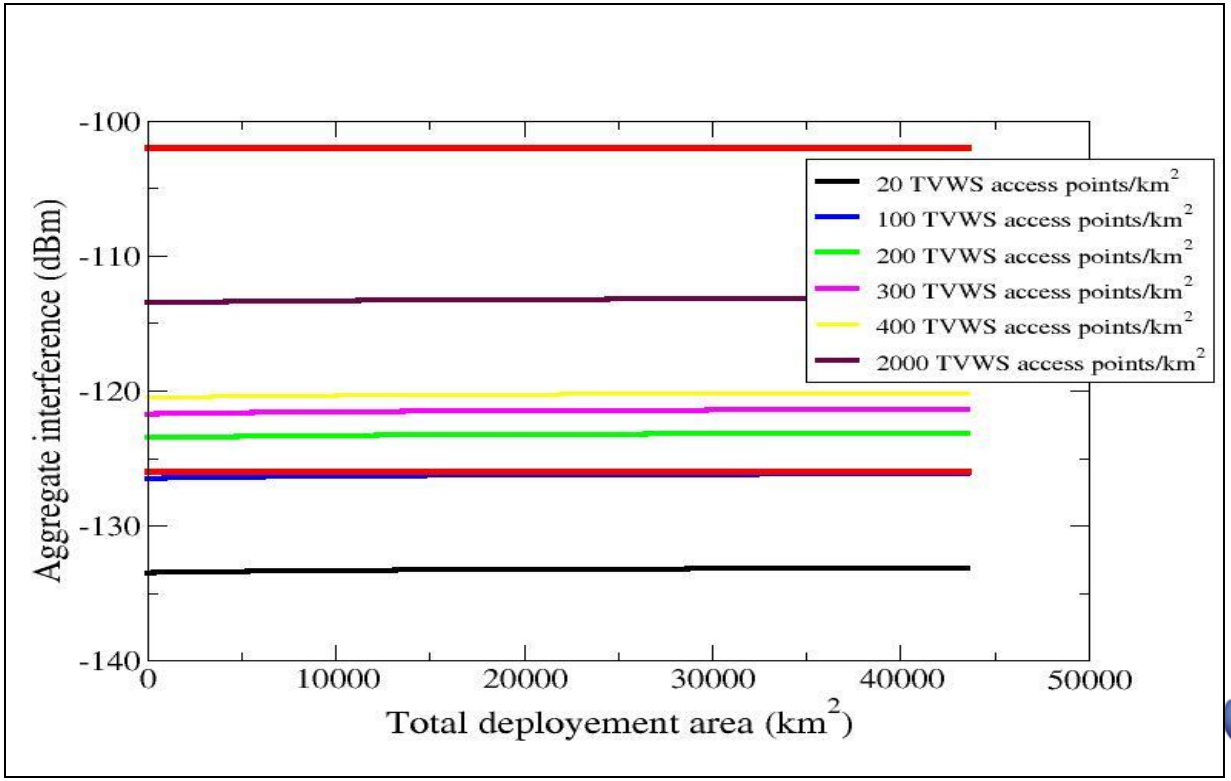
Implications

- Aggregate interference is a function of density and transmit power of cognitive devices (handsets, base stations). These may belong to different service providers and users.
- Mechanism for centralised and distributed aggregate interference estimation
- New centralised and distributed power control algorithms



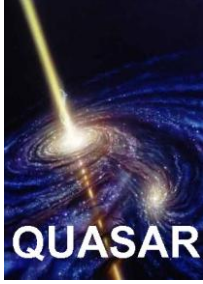
Example: TVWS base station deployment

- TVWS Frequency band: 700 MHZ
- DTT Transmit power: 2KW
- DTT Antenna pattern: isotropic
- Number of available TVWS channels: 12 (96 MHz)
- Channel bandwidth 8MHz
- Transmit power of cognitive radios: 100 mW
- Propagation model: Pathoss ($\alpha = 2.5$).
- Sensitivity threshold of DTT receivers: -72 dBm
- Protection ratio of DTT receivers (the ratio between desired to undesired signal): 30, 54 dB



QUASAR's Initial Research Results

QUASAR Objectives

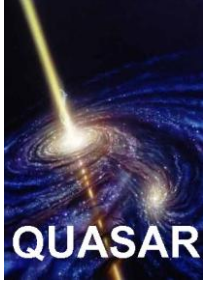


Accessing the Real-world benefits of Cognitive Radio

www.quasarspectrum.eu

1. Investigating the impact of opportunistic spectrum access on **primary system performance**
2. **From "detecting spectrum holes" to the regime of "discovering 'real' spectrum opportunities**" -beyond signal processing into a data fusion problem.
3. Assess impact of **multiple secondary users**.
4. Multi-Parameter and **Utility based assessment of Spectrum value**
5. **Business impact of Secondary spectrum sharing**.
6. Providing specific and reasoned proposals to go **beyond the current regulatory framework** for the whole value-chain

The partners



RWTH AACHEN UNIVERSITY

Ofcom

PTS

Bundesnetzagentur

KTH VETENSKAP OCH KONST

A?

YONSEI UNIVERSITY

Ss. Cyril and Methodius University in Skopje

ERICSSON

Finnish Communications Regulatory Authority

BT

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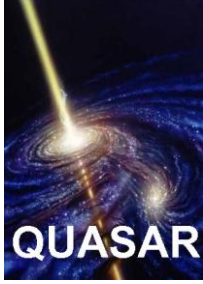
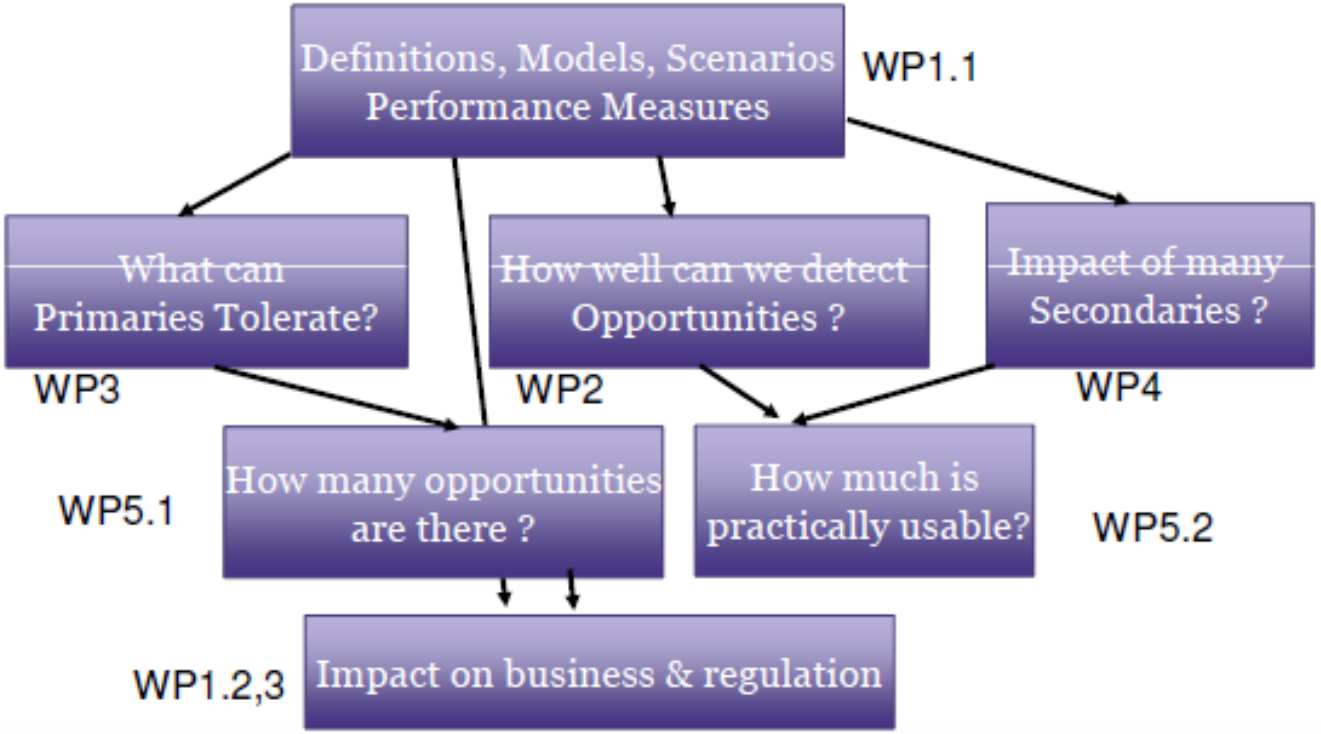
QUASAR: Progrss so far (6 months)





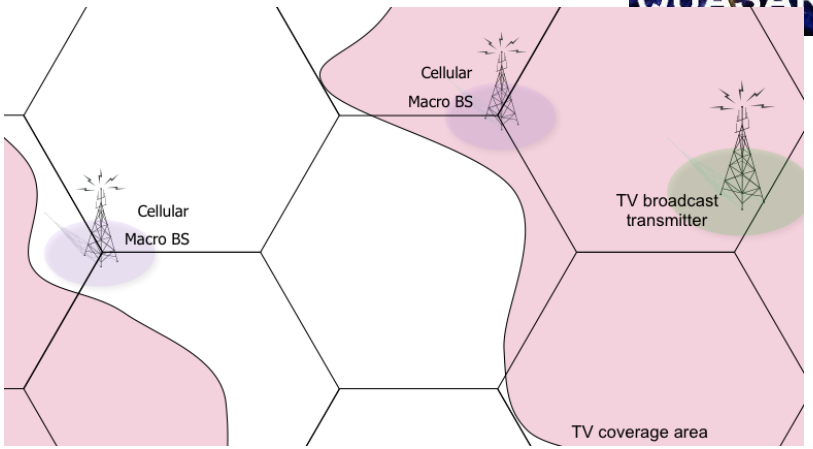
Scenario classification

- **Scenario classification model**
  Developed to find relevant scenarios for secondary spectrum access, based on four main aspects of secondary spectrum access:
  - Secondary spectrum usage type
  - Spectrum sharing type (vertical and horizontal)
  - Primary and secondary license type
  - Level of cooperation

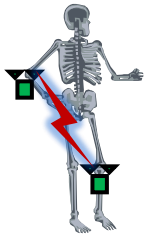
- **Six use case scenarios identified as promising**
  from technical, business and feasibility point of view

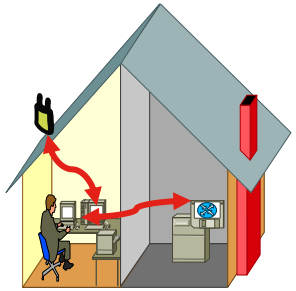
Main scenario themes

- **Wide area wireless secondary usage**
  Extension of cellular services to secondary spectrum, providing WiFi coverage from indoor to outdoor, M2M communication

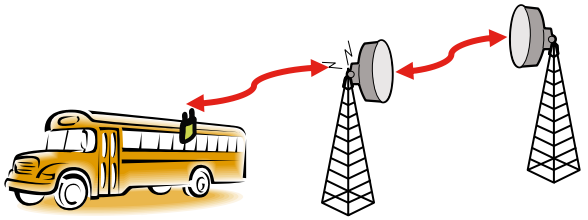


- **Low power indoor secondary usage**
  M2M communication and indoor wireless broadband connectivity

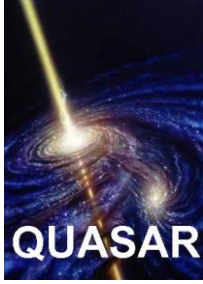




- **Wireless backhauling and relaying using spectrum opportunities**
  Includes relaying to mobile relays



Focus spectrum bands



- **TV broadcasting band (470-790 MHz)**

  Quantitative assessments of the amount of useful spectrum opportunities and business feasibility still lacking (at least in Europe)

- **Aeronautical band for DME (960-1215 MHz)**

  Primary system may allow for a significant amount of spectrum opportunities

- **Radar band (2700-3100 MHz, 5250-5850 MHz)**

  Predictable sweep patterns and fixed radar locations will likely allow a lot of useful spectrum opportunities

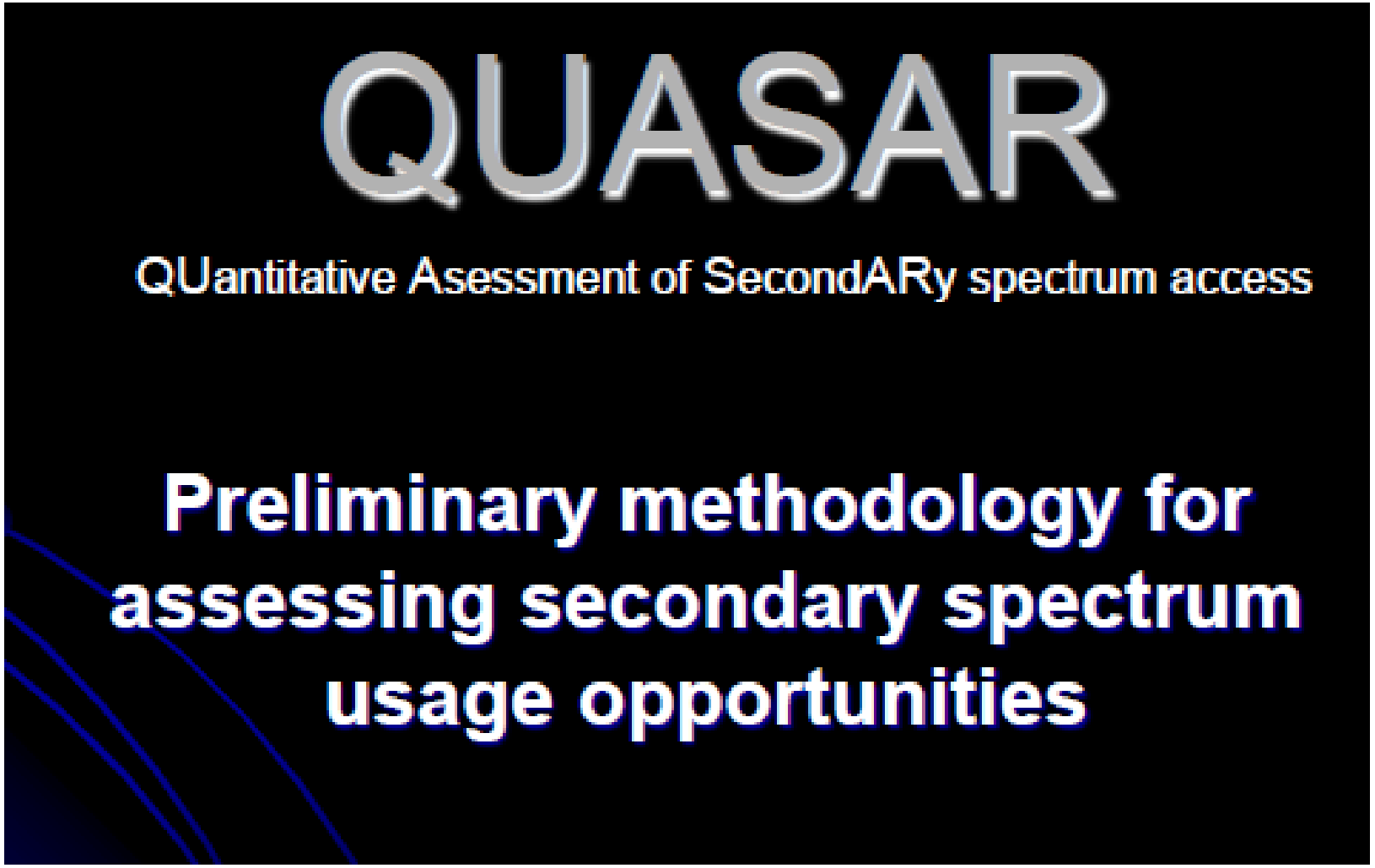
Ch 21 occupancy (blue) and availability (the rest) in Sweden

Secondary sharing methods

- N. Devroye, P. Mitran, V. Tarokh, Fundamental limits of cognitive radio networks , IEEE Trans. Information Theory, 2006
- J. Sachs, I. Maric, A. Goldsmith, Cognitive cellular systems in TV spectrum , Proc IEEE DySPAN 2010
- S. Jayaweera and T. Li, Dynamic spectrum leasing in cognitive radio networks via primary-secondary user power control , IEEE Trans wireless communications, 2009
- M. Marcus, Cognitive radio under conservative regulatory environments , Proc. IEEE DySPAN 2010
- P. Marshall, DSA as a mechanism for transition to interference tolerant systems IEEE DySPAN 2010

Cooperation Level (PU-SU) / Sharing Method	None	Low	High
Interweaved	Sensing-based TVWS Sensing-based radar	Geolocation-based TVWS Geolocation-based radar	
Overlay			Interference leasing /Interference compensation
Underlay	UWB		

Deliverable available from www.quasarspectrum.eu



Definition of the spectrum opportunity

- Definition of the metrics for measuring the spectrum opportunity
  - Specifying what the spectrum opportunity means
  - Specifying how to compute the spectrum opportunity
- Ideal spectrum opportunity computation
- Spectrum opportunity computation by using different approaches for spectrum allocation
  - Different amount of available information
  - Ideal spectrum allocation
  - Database based spectrum allocation
  - Sensing based spectrum allocation

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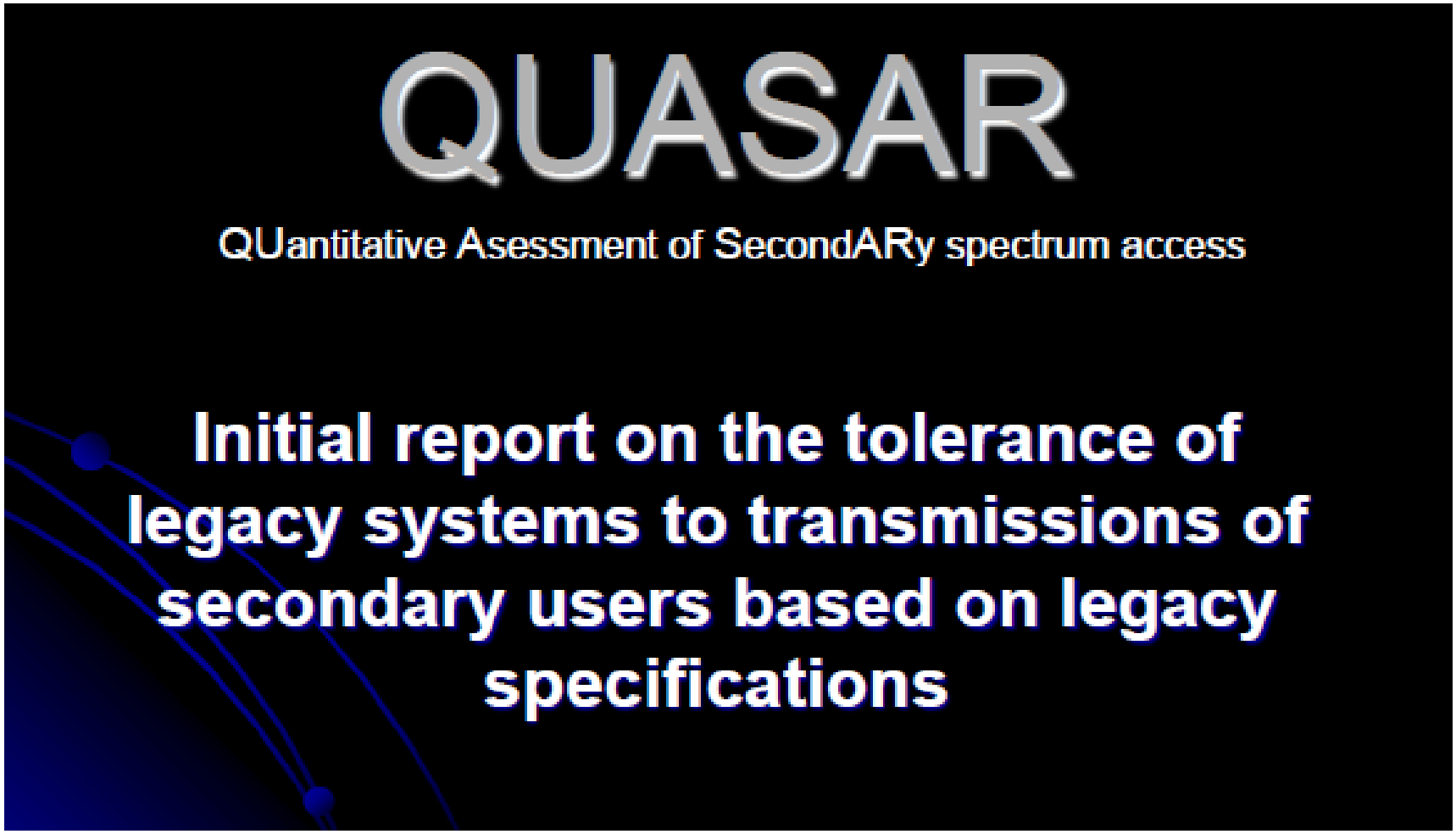


Three primary systems

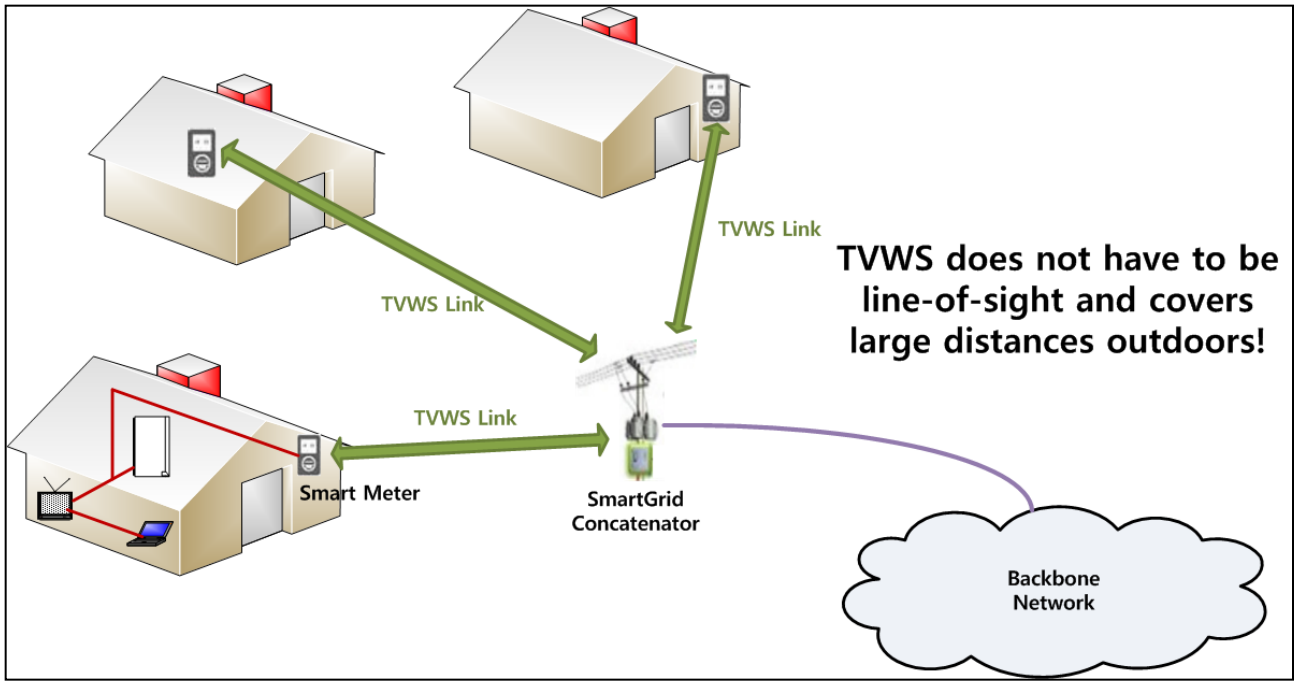
- Three licensed primary systems are studied, namely digital video broadcasting, radar and aeronautical systems.
- The impact of interference is evaluated as a function of Desired to Undesired Power level (D/U) ratio for DVB systems, the pulse detection error for Aeronautical systems and the maximum interference-to-noise ratio (INR) for Radar systems.

Initial conclusions

- Co-channel and adjacent channel interference need to be taken into account.
- Same tolerance limits can be used for non-continuous bursty-type users as for continuous data traffic users.
- The total amount of interference caused by multiple interferers should be kept below the desired signal level.
- For aeronautical systems, spatial separation and transmit power of the secondary system determine the feasibility of secondary usage.
- For other radar systems also the INR value and the IF separation effects determine the possibilities for secondary users.
- Watch this space! www.quasarspectrum.eu

Backup Slides

Use case 4: smart metering and smart grids



- A two-tier architecture using Zigbee for HAN and TVWS
- Cellular solutions not designed for this application
- TVWS offers good penetration and scope for high number of low bandwidth links

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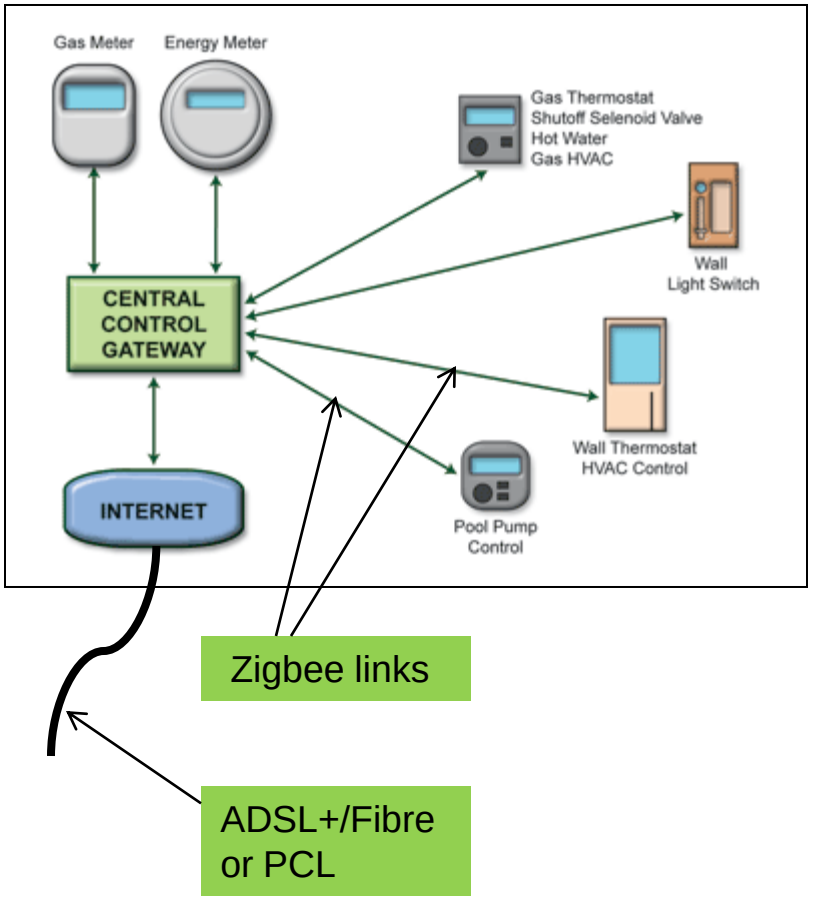
Use case 4: Smart metering and grids

- UK government's smart grid project aims to cover 28 million homes and businesses by 2012.
- Two levels (tiers) of communication for smart grids are envisaged
  - Communication between smart meters and devices in the home via a Home Area Network (HAN)
  - Communication delivered from/to home via a Wide Area Network (WAN).
- Zigbee for HAN combined with ADSL+/Fibre-to-home for WAN is the most likely fixed-line solution. The shortcomings are:
  - No support for mobility (e.g. for utility companies' engineers)
  - Doesn't work in areas where broadband is not available.
  - Whole-home indoor using Zigbee operating in 2.4 GHz could be problematic.



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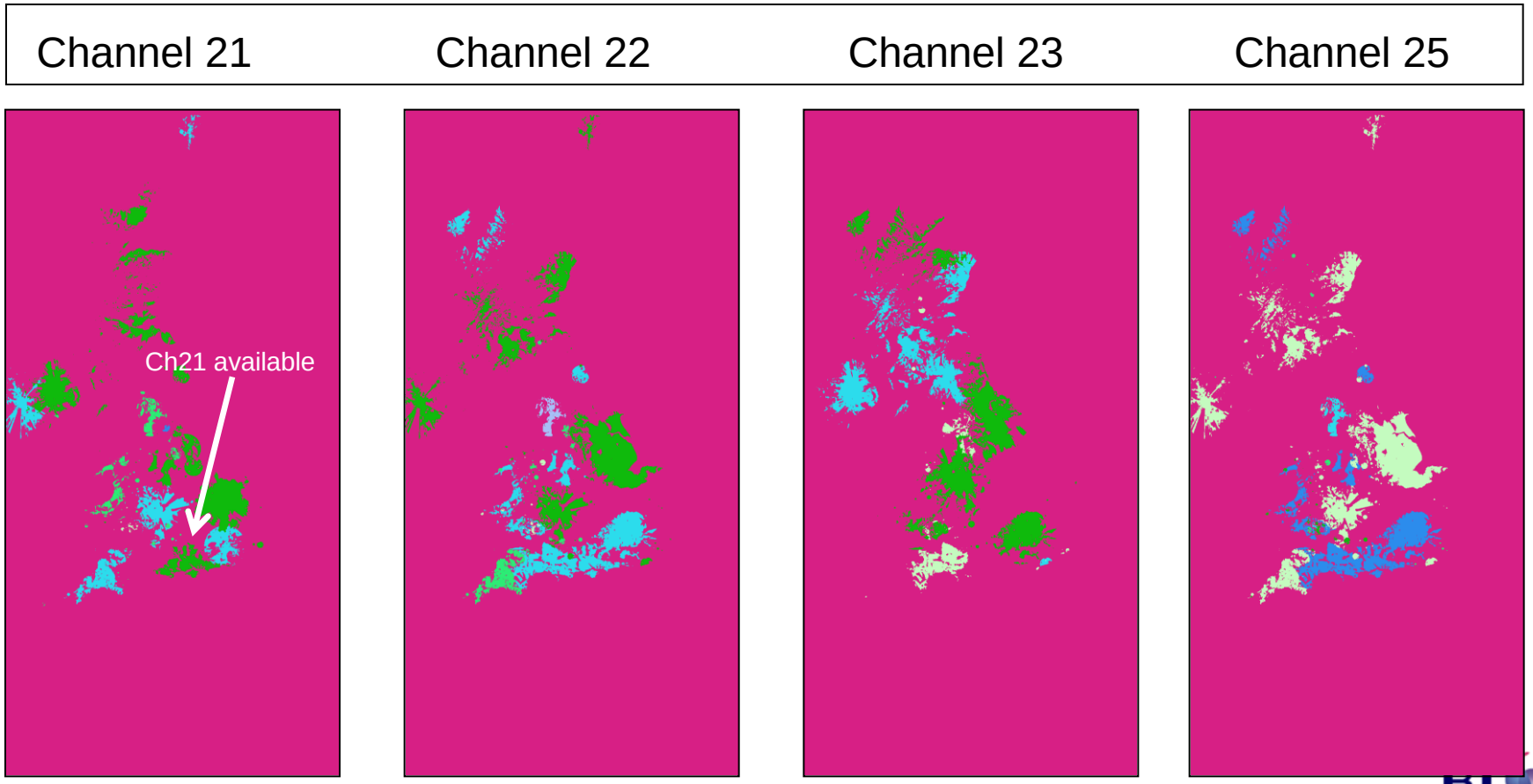
DTT coverage maps



Wi-Fi signal at 760 MHz generated using Ubiquiti Router Station Pro board and XR7 Radios