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White Spaces Across London

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On behalf of our trial – see acknowledgement slides at end for range of contributors

Please refer to back-up slides at the end of this presentation for more detailed content—these slides will be made available after the event

Glasgow TV White Spaces Pilot Event
Glasgow, UK, 14 May 2015

Overview

- Ofcom/ETSI Framework: White Spaces in the UK
- Our Trial
- So, What is Achievable in TV White Space?
  - Availability, capacity and aggregation studies
  - Experimental work / performance testing
- Conclusion

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Ofcom/ETSI Framework: White Spaces in the UK

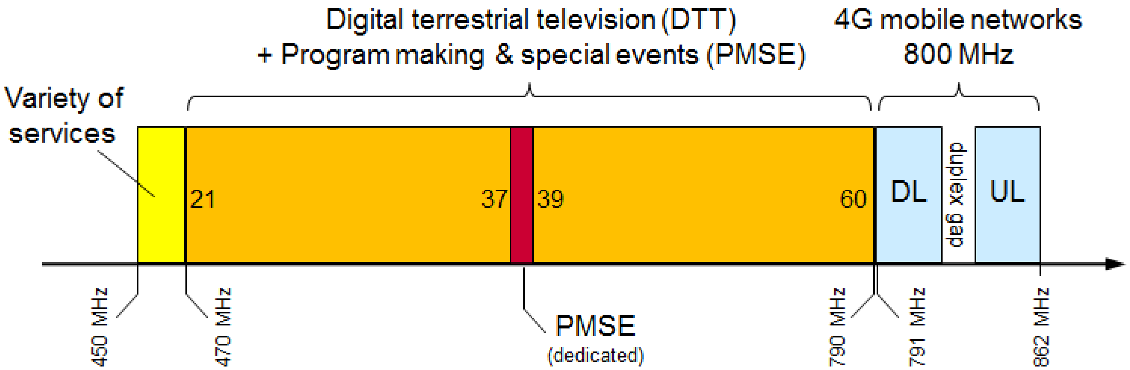
(far more detail in back-up slides at end of presentation)

Which Frequencies? –Bandwidth?

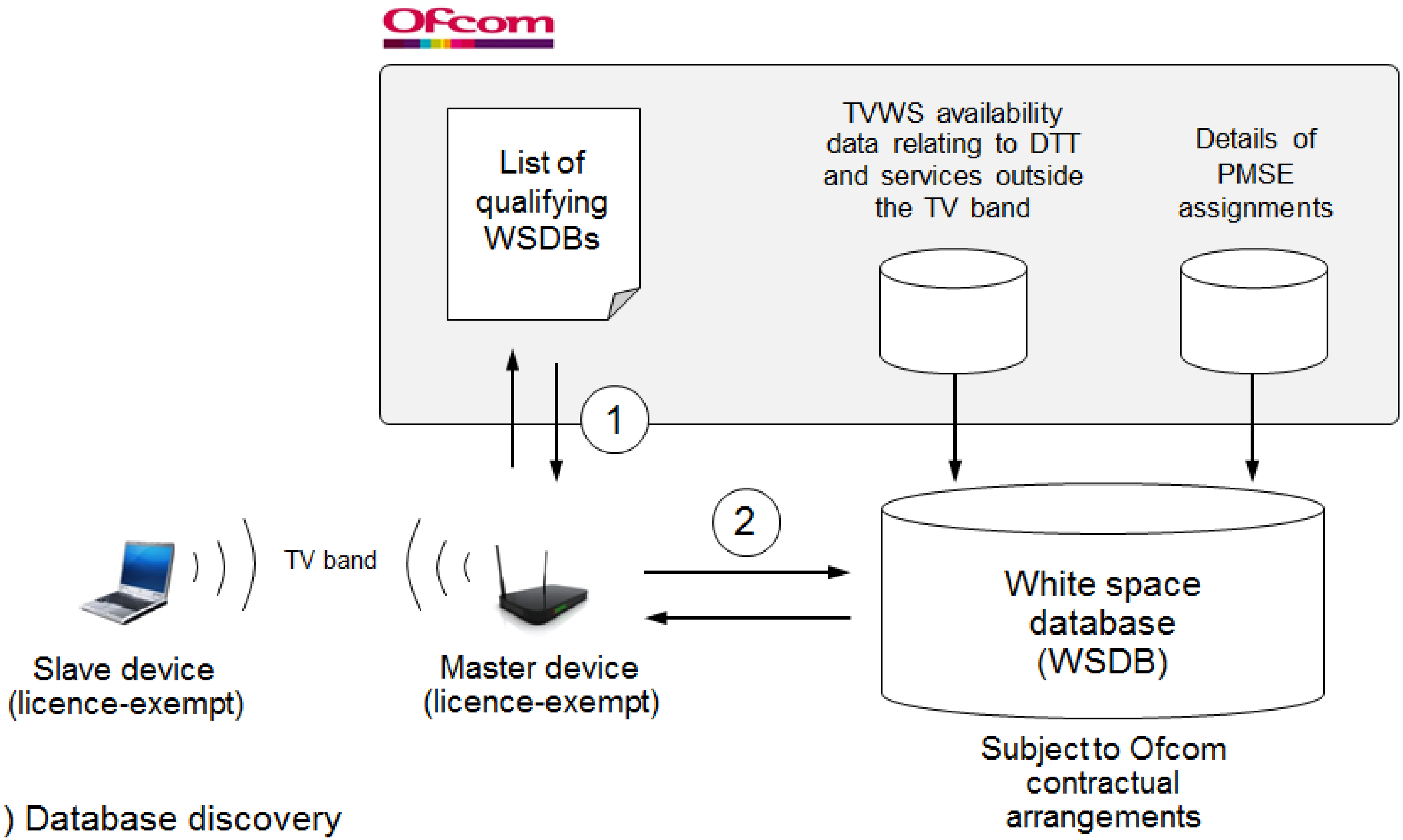
- 470-790 MHz
  - 320 MHz total; **312 MHz** excluding shared PMSE channel 38
  - 694(exact value TBD)-790 MHz approved for co-primary mobile broadband in ITU Region 1 (includes UK) with rules to be decided in WRC 2015; if all this spectrum were removed would leave us with **216 MHz** in the UK
  - Compares with a sum of **300 MHz** in the 54-72, 76-88, 174-216, and 470-698 MHz VHF/UHF bands in US (Region 2—Region 3 similar)

- 8 MHz channel raster – channel numbers 21 (474 MHz centre frequency) to 60 (786 MHz centre frequency); compares with 6 MHz channel raster and channel numberings 2-51 in US (Region 2—Region 3 similar)
  - Current UK trials limited to channels 22 to 59 (of course excluding channel 38) to help protect services that are next to TV frequencies

- Channel 38 (606-614 MHz) reserved exclusively for shared PMSE usage. Cannot be used by white space devices



Database Discovery and Device-Database Communications



1) Database discovery
2) Device-database communications.

Emissions Requirements—In TV Bands (and *key* differences from US)

- Ofcom/ETSI define 5 classes of devices' ACLR performance
  - Better ACLR performance means less interference in adjacent channels hence typically the ability to transmit at higher EIRP without violating adjacent channels interference limits

- Variable maximum EIRPs are given to devices, thereby allowing them to transmit (at reduced EIRP) in many locations that they wouldn't be able to under the US rules

- **These are key differences from US case, giving a lot of flexibility**, with devices of even relatively poor ACLR performance and in poor locations being able to use white space with appropriate powers

- Noted that power in 100kHz chunks in adjacent channels is compared with power in 8 MHz intended channel. Already 80x (approx. 19dB) lower. I.e., -74 dB here is equivalent to -55 dB in terms of power spectral density

$$P_{OOB}\,(\mathrm{dBm}/(100\ \mathrm{kHz})) \leq \max\{\, P_{IB}\,(\mathrm{dBm}/(8\ \mathrm{MHz})) - \mathrm{ACLR}\,(\mathrm{dB}),\ -84\,(\mathrm{dBm}/(100\ \mathrm{kHz}))\,\}$$

Where P_{OOB} falls within the nth adjacent DTT channel (based on 8 MHz wide channels)	ACLR (dB)				
	Class 1	Class 2	Class 3	Class 4	Class 5
n = ±1	74	74	64	54	43
n = ±2	79	74	74	64	53
n ≥ +3 or n ≤ -3	84	74	84	74	64

Latest Developments

- Ofcom initiated a large pilot of this technology in the UK, with 9 triallists participating
- Initial schedule was hoped to be from October 2013 for approx 6 months
- In practice, real work on the pilot started with the qualification of the first databases in May/June 2014
- Pilot remains ongoing, at least continuing until early 2015 and likely a lot later than that
  - Currently testing white space devices from Adaptrum, Carlson Wireless, InterDigital, Runcom, Eurecom, 6Harmonics, KTS Wireless/Sinecom, Mediatek, MELD, Neul and NICT
  - 8 Geolocation databases now qualified: Spectrum Bridge, Fairspectrum, NICT, Nominet, Google, Sony, iconectiv and Microsoft

Latest Developments

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- Ofcom have done their own investigations and published studies on, e.g., coexistence testing of white space devices with DTT and PMSE, protection ratio analysis, coupling ratio studies, intermodulation studies, etc., in November and December 2014 (see next slide)
- Ofcom released a statement on the pilot on 12 February, confirming that it is approving of white spaces on a license-exempt basis, providing some background (e.g., testing) information and comment on the progress of the pilot, and outlining some tweaks to the framework
- Published consultation on manually configurable white space devices, requiring licensing of those whereby their operation will be according to exactly the same TV white space framework (fully-automated devices, e.g., those with integrated GPS, are license-exempt) (see next slide)
- Current estimate (Ofcom have changed this from estimates late last year) is that Ofcom expect the system to go live towards the end of this year. The pilots are continuing at least throughout 2015

Ofcom Statement (12 February)

- “Implementing TV White Spaces”, February 2015
  - http://stakeholders.ofcom.org.uk/consultations/white-space-coexistence/statement

- Ofcom have approved license-exempt TV white space devices
  - “This document sets out Ofcom's decision to allow a new wireless technology access to the unused parts of the radio spectrum in the 470 to 790 MHz frequency band. Our decision follows extensive consultation with stakeholders and a pilot.”

- Covers numerous aspects, including
  - An overview of aspects of the UK TV white spaces framework
  - The TV White Spaces Pilot including details and observations from that
  - Detail on white space device assumptions/capabilities necessary to authorise devices to operate on license-exempt basis in TV white spaces
  - Ofcom’s approach to coexistence with DTT and PMSE
  - Assessment of white space availability in some particular areas
  - Next steps to the commercial realisation of the technology

Ofcom Statement (12 February)

- Appendices covering numerous interesting aspects
  - Detail on the Ofcom white space device emissions limits calculation process for aspects of the framework
    - Protection of PMSE (including location-agnostic shared PMSE channel 38)
    - Protection of DTT
    - Protection of mobile services above TV bands
    - Protection of services below TV bands
    - Cross-border protection
  - Work on protection ratios analysis for DTT and PMSE
  - Summary of responses to Ofcom's consultations, and Ofcom's comments
- Linked to provided drafts of the Ofcom "Statuatory Instruments" (regulations) and interface requirements documents to realise license-exempt TV white space devices in the UK

ETSI EN 301 598, Key Ofcom Consultations and other Publications

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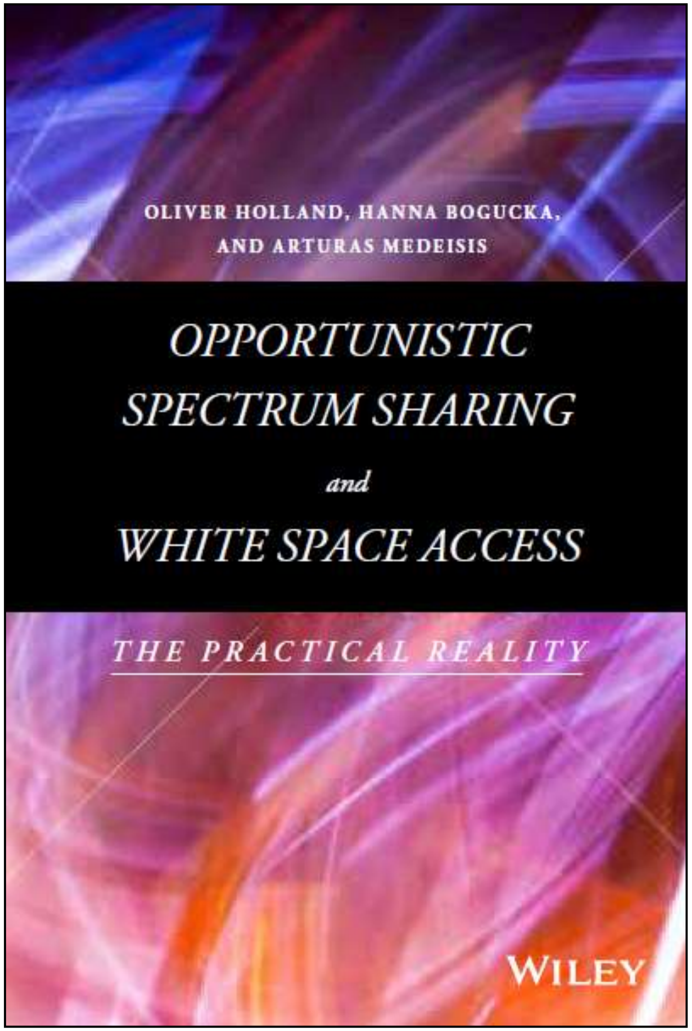
- White Space Device white space device conformance requirements defined in ETSI EN 301 598; heavy input of Ofcom in creating that standard
  - http://www.etsi.org/deliver/etsi_en/301500_301599/301598/01.01.01_60/en_301598v010101p.pdf
- Key Ofcom consultations (see http://stakeholders.ofcom.org.uk/spectrum/tv-white-spaces)
  - “TV white spaces: approach to coexistence”, September 2013 (also note addendum from October 2013)
    - http://stakeholders.ofcom.org.uk/consultations/white-space-coexistence
  - “TV white spaces - A consultation on white space device requirements”, November 2012
    - http://stakeholders.ofcom.org.uk/consultations/whitespaces
  - “Implementing Geolocation”, November 2010
    - http://stakeholders.ofcom.org.uk/consultations/geolocation
  - “Manually configurable white space devices”, February 2015
    - http://stakeholders.ofcom.org.uk/consultations/manually-configurable-wsds
- Ofcom coexistence studies
  - “TV White Spaces: PMSE coexistence tests – technical report”, November 2014
    - http://stakeholders.ofcom.org.uk/market-data-research/other/technology-research/2014/tvws-pmse-coexistence
  - “TV White Spaces: DTT coexistence tests – technical report”, December 2014
    - http://stakeholders.ofcom.org.uk/market-data-research/other/technology-research/2014/tvws-coexistence-tests
- Ofcom statement on allowance of license-exempt white space devices
  - “Implementing TV White Spaces”, February 2015
    - http://stakeholders.ofcom.org.uk/consultations/white-space-coexistence/statement

Book

- A detailed coverage of aspects of TV white spaces and other solutions for opportunistic spectrum sharing
- O. Holland, H. Bogucka, A. Medeisis (Eds.), *Opportunistic Spectrum Sharing and White Space Access: The Practical Reality*, Wiley
- Available imminently
- Chapters include (among many other high quality contributions)
  - H. R. Karimi, “UK framework for access to TV white spaces”
  - J. Schmidt, P. Stanforth, “Spectrum Sharing using Geo-location Databases”



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Our Trial

(far more detail in back-up slides at end of presentation)

Objectives (Including Longer-Term Aspirations)

- To test communications systems and scenarios that may be implemented in TV White Space
  - LTE multicast/broadcast (eMBMS)
  - Broadband for public protection and disaster relief
  - TD-LTE and other TDD systems for more general applications in TV White Space (e.g., general broadband provisioning, and small cells in TV White Space)
  - WiFi in TV White Space (802.11af draft)
  - Wireless backhaul links in TV White Space
  - M2M implementations (possible future work)
- To support the development/assessment of the ETSI EN 301 598 standard, and assessment of white space devices

Objectives (Including Longer-Term Aspirations)

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- To test the correct performance of the UK’s TV White Spaces framework in general
- To carry out research studies using TV White Space implementations
  - Aggregation of resources/links (e.g., TV White Space with licensed and other unlicensed such as ISM, and links within TV White Space)
    - Development of methods to assist aggregation, e.g., MAC solutions, intelligent database-assisted solutions
    - Qualitative and quantitative performance surveys
  - Secondary coexistence (e.g., LTE coexisting and 802.11af in TV White Space, and multiple instances of different standards/devices coexisting)
  - To undertake studies and surveys on the performances that are achieved, e.g., in terms of interference to primary (!), secondary user performance through objective user opinion polling
  - Spectrum monitoring and assessment (e.g., spatial and temporal effects on the spectrum—correlation)

Our White Space Devices

- Numerous white space devices participating in our trial at different times; some available on a longer-term basis, some available for specific durations
  - Carlson Wireless RuralConnect
    - Proprietary waveform
  - KTS/Sinecom Agility White Space Radio (AWR)
    - Proprietary waveform
  - Eurecom/King's College white space devices
    - LTE in TVWS; other waveforms possible
  - NICT WiFi (802.11af) white space devices
  - NICT LTE in white space devices
  - InterDigital WiFi white space devices (can aggregate up to 4 non-contiguous channels)
  - Runcom WiMAX white space devices (can aggregate up to 4 non-contiguous channels)

Our Utilised Geolocation Databases

- Noted that the interfaces between TV White Space devices and geolocation databases are not standardised. It is therefore typically the case that particular TV White Space device manufacturers are working with particular databases
- We are using a range of databases in our trials
  - Fairspectrum → Carlson Wireless and Eurecom devices
  - NICT → NICT and Eurecom devices
  - Spectrum Bridge → InterDigital devices, KTS/Sinecom devices
  - Joint Research Centre of the European Commission → for comparison using a range of devices, not deployed in UK
- Also interacting or working to various extents with the following
  - Nominet (although mostly within a dedicated additional trial that Nominet has specifically set up with us)
  - Sony
  - BT (there have been discussions, current status is unknown on whether they will move to qualification for participation in Ofcom Pilot)

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Locations

- Extensive range of locations, covering almost all imaginable environments, tested (mostly) sequentially
  - Cluttered vs. non-cluttered
  - High incumbent systems TV bands usage vs. relatively low usage
  - A range of propagation characteristics

- Almost exclusively campuses/buildings among the range of universities that are collaborating in our trials

So, What is Achievable in TV White Space?

—Availability/Capacity

(far more detail in back-up slides at end of presentation)

Availability and Capacity

- Have adapted one of our implementations of white space device side to methodically query Fairspectrum to obtain information on available white space, and do capacity analyses with particular emphasis on aggregation. Of course, not taking into account Ofcom framework changes, which are not yet implemented
  - London M25 area, top-left corner (lat, lon) 51.678064, -0.506744, bottom-right corner 51.312133, 0.22934, sampling “spatial frequency” 0.01 degrees equally in latitude and longitude. 2,775 samples total for each of the assessments on a London-area basis

Availability and Capacity

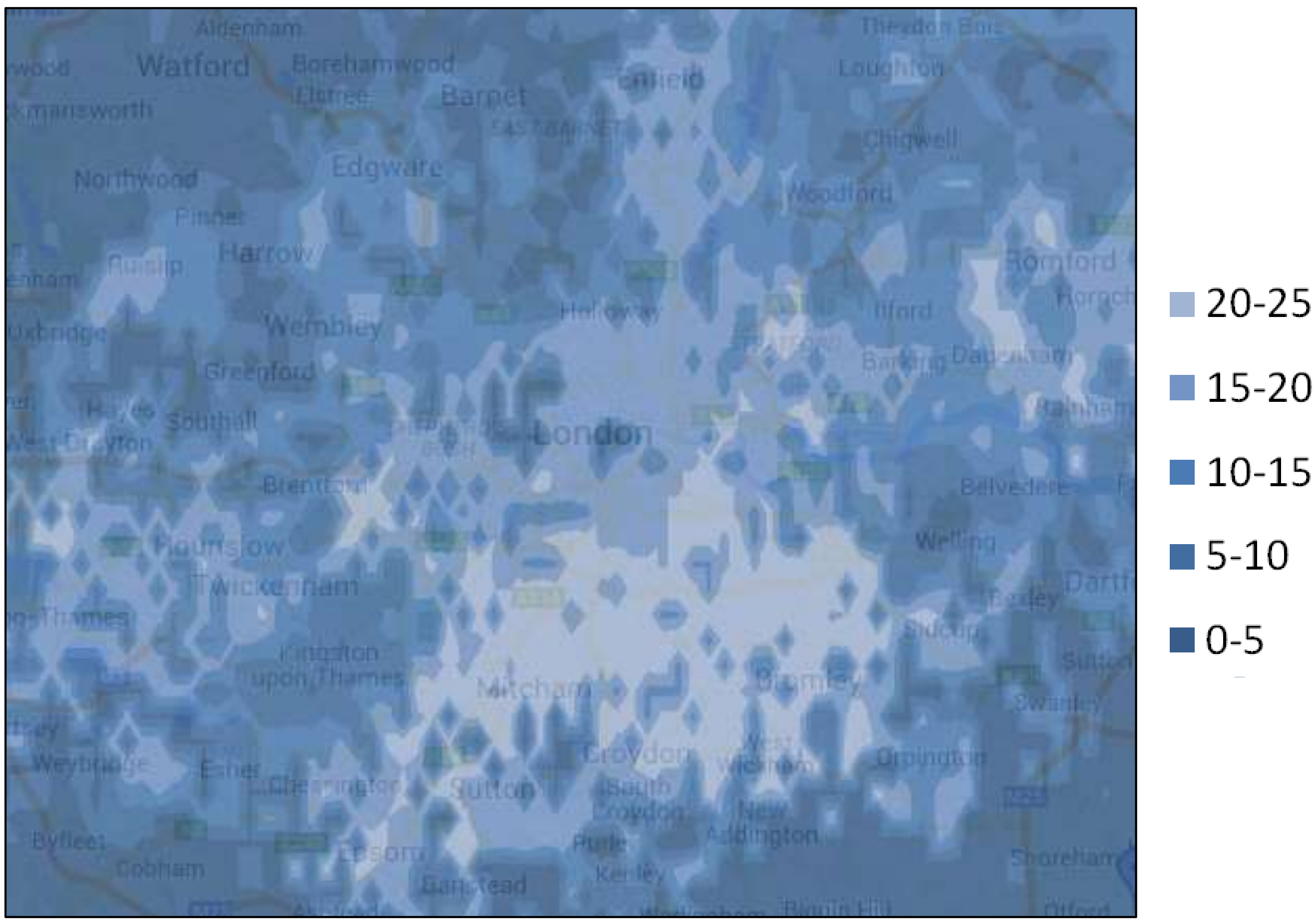
- Scenario configurations

Scenario	Transmitter Height (m)	Receiver Height (m)	Transmission Distance (m)	Path loss	Shannon Efficiency
Mobile Broadband Downlink	30	1.5	2,000	Hata Urban, large city	0.5
Indoor Wireless Local Area Networking	1	1	80	Yamada model, 8 walls, same floor, King's College Strand parameters [1]	0.5

[1] W. Yamada, …, O. Holland, et al., "Indoor Propagation Model for TV White Space," CROWNCOM 2014, Oulu, Finland, June 2014.

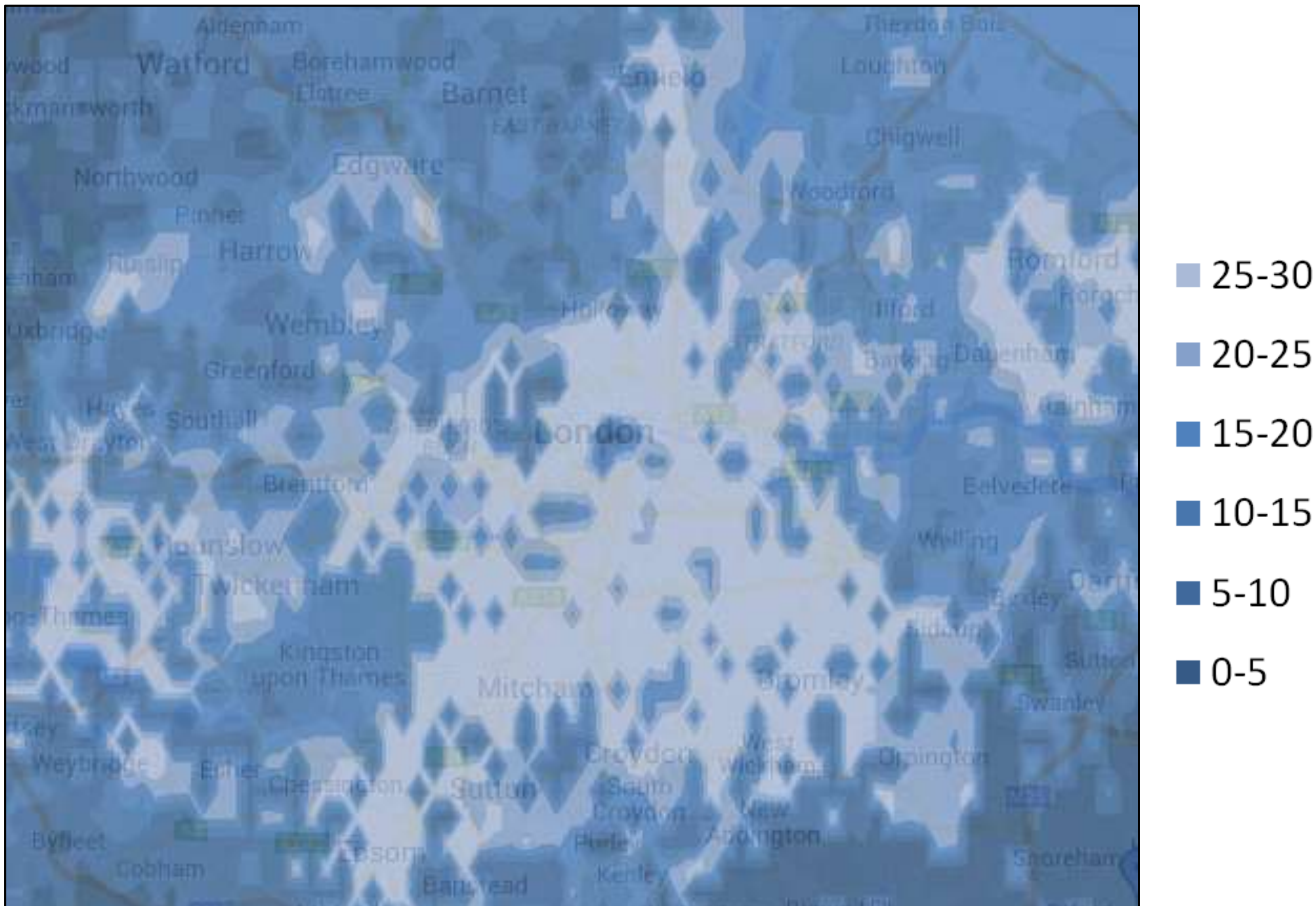
Availability—Number of Channels

- At least 30 dBm allowed EIRP – “Mobile Broadband Downlink” scenario, Class 5, London M25 area



Availability—Number of Channels

- At least 30 dBm allowed EIRP – “Mobile Broadband Downlink” scenario, Class 1, London M25 area

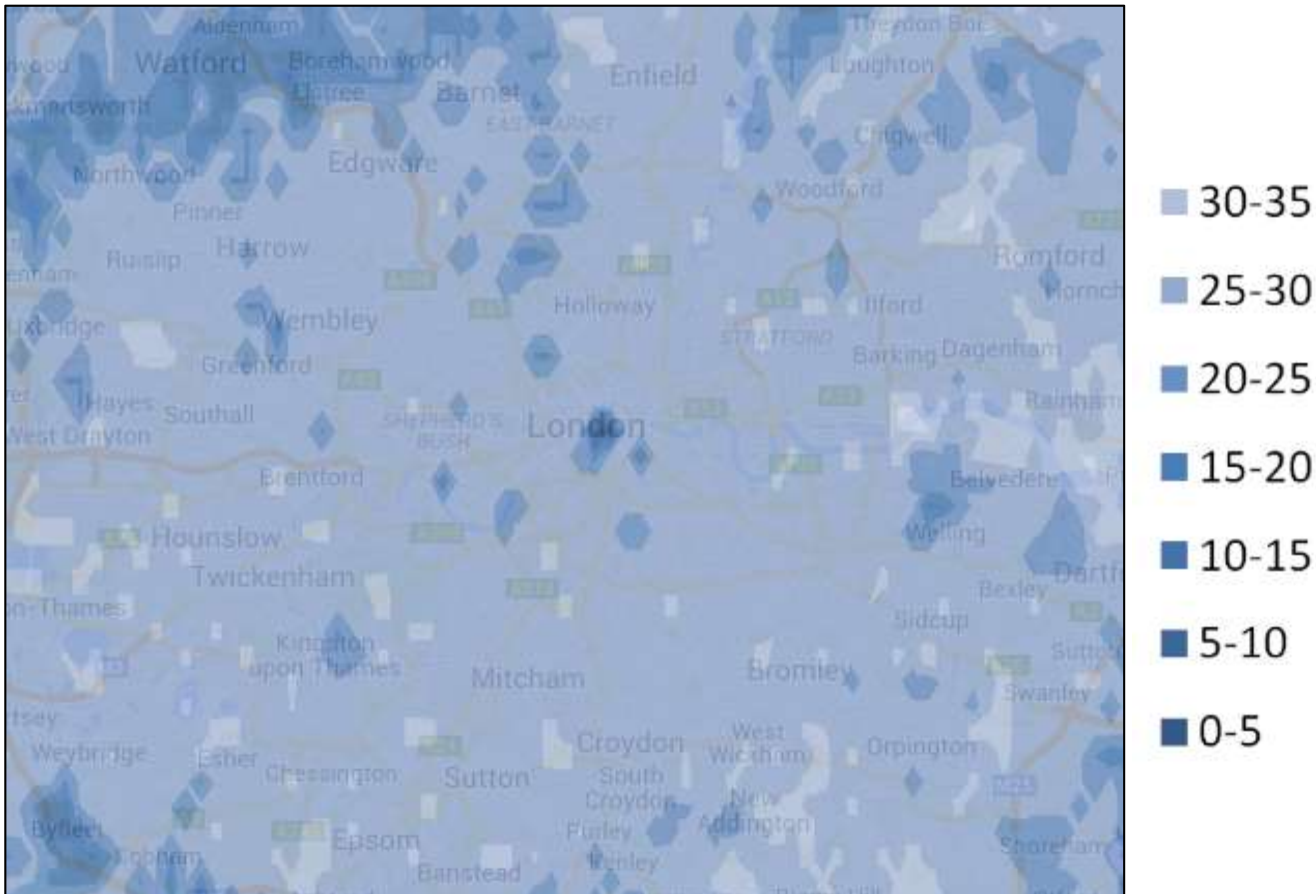


Availability—Number of Channels

- For comparison: at least 20 dBm allowed EIRP – “indoor Wireless Local Area Networking” scenario, Class 5, London M25 area

Availability—Number of Channels

- For comparison: at least 20 dBm allowed EIRP – “indoor Wireless Local Area Networking” scenario, Class 1, London M25 area



Availability—Number of Channels

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- At least 30 dBm allowed EIRP – “Mobile Broadband Downlink” scenario, London M25

Number of channels

	Class 1	Class 2	Class 3	Class 4	Class 5
Average	15.6	15.4	15.2	12.6	10.2
STD	8.4	8.4	8.5	8.1	7.1
CoV	0.54	0.55	0.56	0.64	0.70

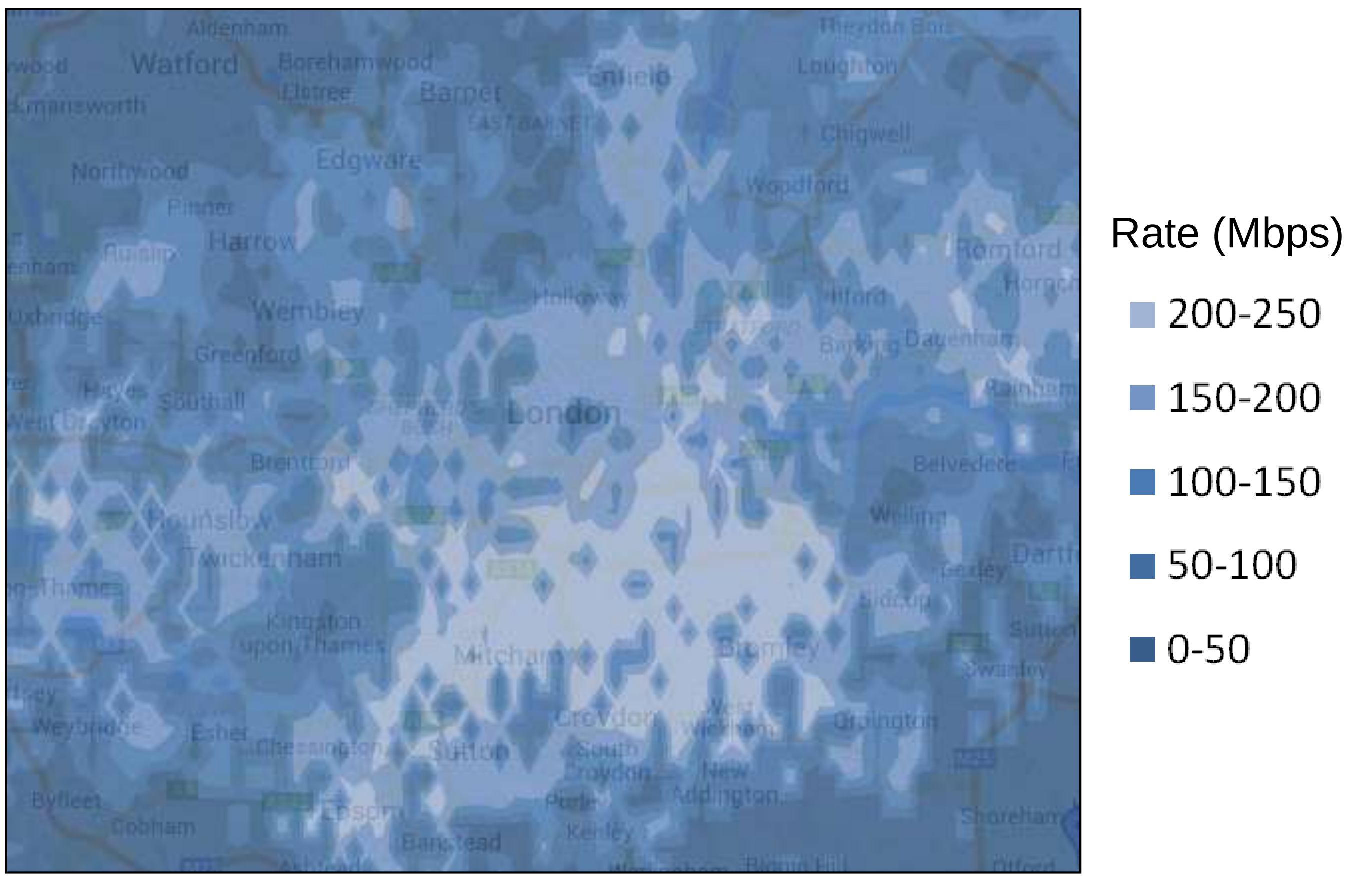
- At least 20 dBm allowed EIRP – “Indoor Wireless Local Area Networking” scenario, London M25

Number of channels

	Class 1	Class 2	Class 3	Class 4	Class 5
Average	25.7	25.6	25.5	24.9	23.4
STD	3.4	3.4	3.6	4.2	5.2
CoV	0.13	0.13	0.14	0.17	0.22

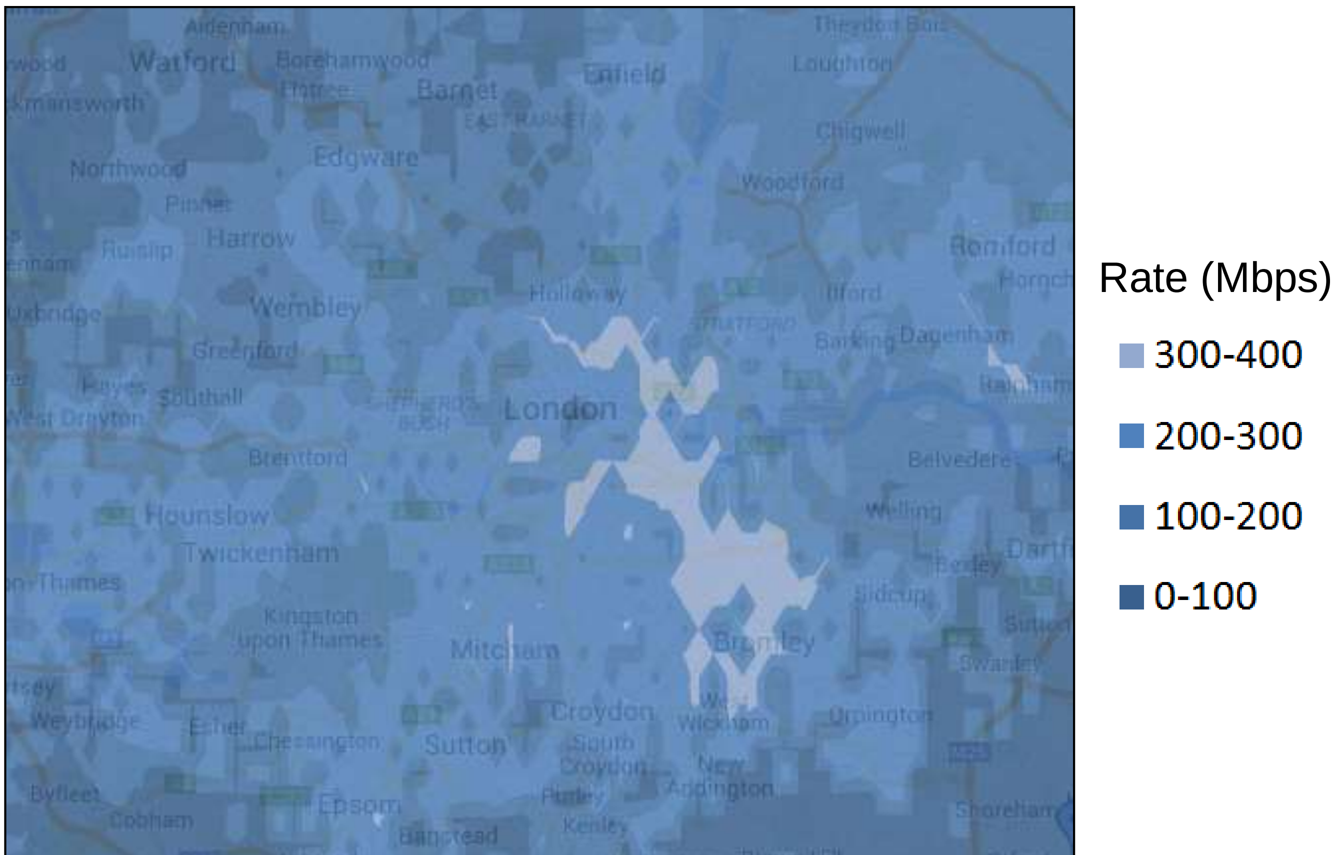
Capacity Through Aggregation

- Optimally aggregating all available channels at maximum allowed EIRP on a per-channel basis, London M25 area, Class 5, Mobile broadband downlink scenario



Capacity Through Aggregation

- Optimally aggregating all available channels at maximum allowed EIRP on a per-channel basis, London M25 area, Class 1, Mobile broadband downlink scenario



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Capacity Through Aggregation

- Optimally aggregating all available channels at maximum allowed EIRP on a per-channel basis, London M25 area, Class 5, Indoor Wireless Area Networking scenario

Capacity Through Aggregation

- Optimally aggregating all available channels at maximum allowed EIRP on a per-channel basis, London M25 area, Class 1, Indoor Wireless Area Networking scenario

Capacity Through Aggregation

- "Mobile Broadband Downlink" scenario, London M25 area

Achieved Rate (Mbps)

	Class 1	Class 2	Class 3	Class 4	Class 5
Average	167.0	165.1	155.4	130.9	104.7
STD	84.2	84.4	82.5	77.4	66.8
CoV	0.50	0.51	0.53	0.59	0.64

- "Indoor Wireless Local Area Networking" scenario, London M25 area

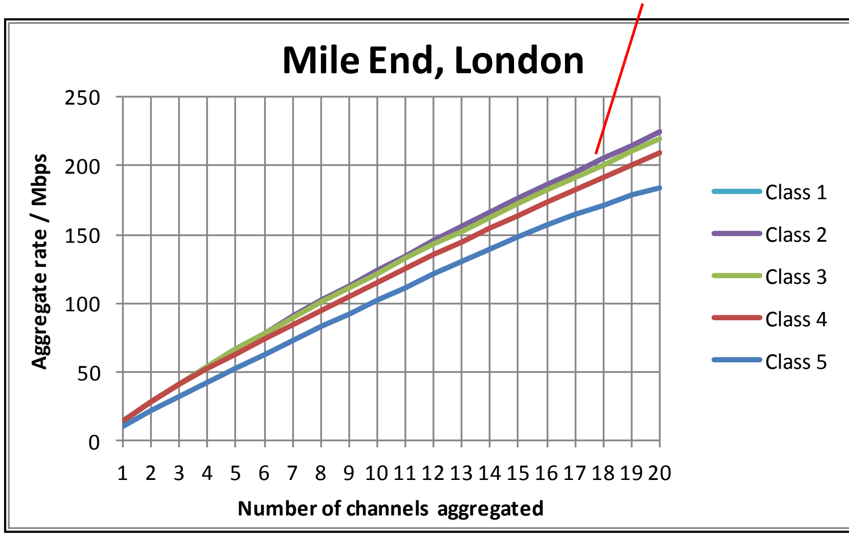
Achieved Rate (Mbps)

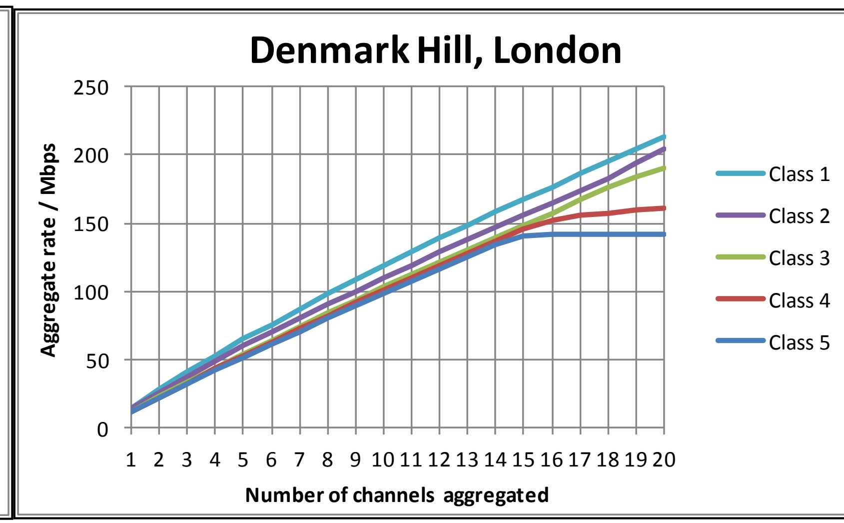
	Class 1	Class 2	Class 3	Class 4	Class 5
Average	333.5	330.9	327.5	312.5	285.6
STD	54.9	55.6	58.8	65.4	67.9
CoV	0.16	0.17	0.18	0.21	0.24

Capacity Through Aggregation

- "Mobile Broadband Downlink" scenario
  - Channel selection rule: Max power, and if power is equal then lowest frequency. Contiguous or non-contiguous (unlimited radios/filtering)

Classes 1 and 2 identical





Capacity Through Aggregation

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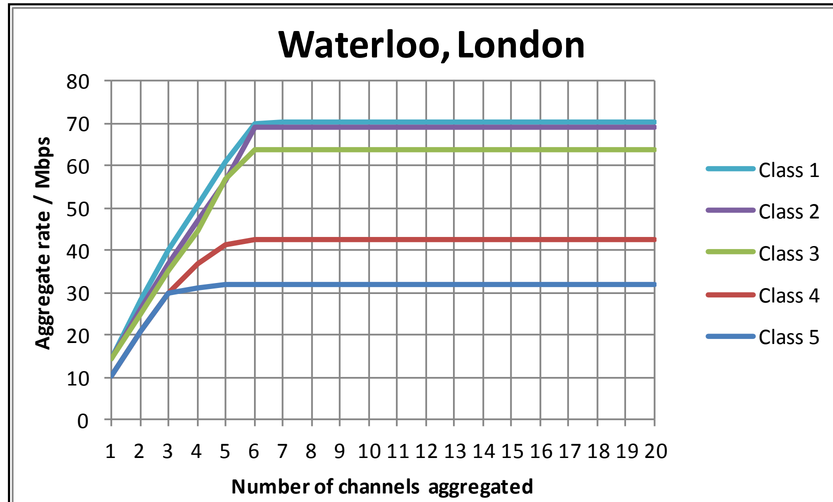
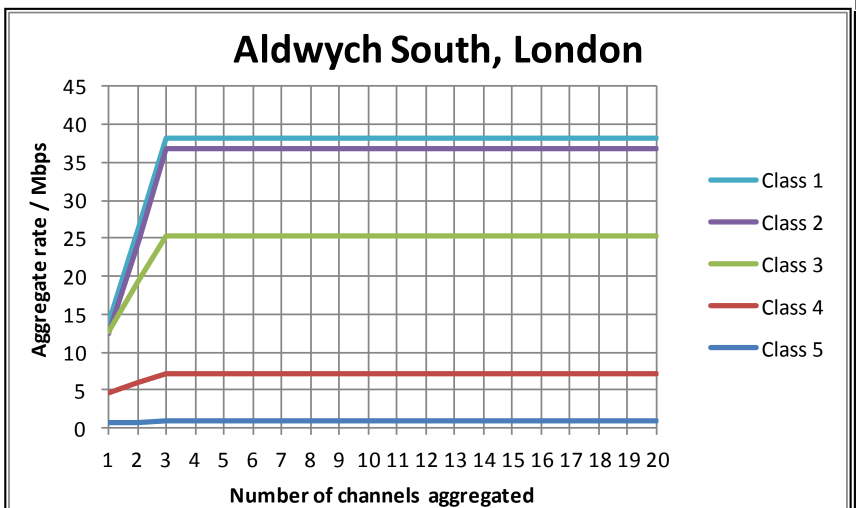
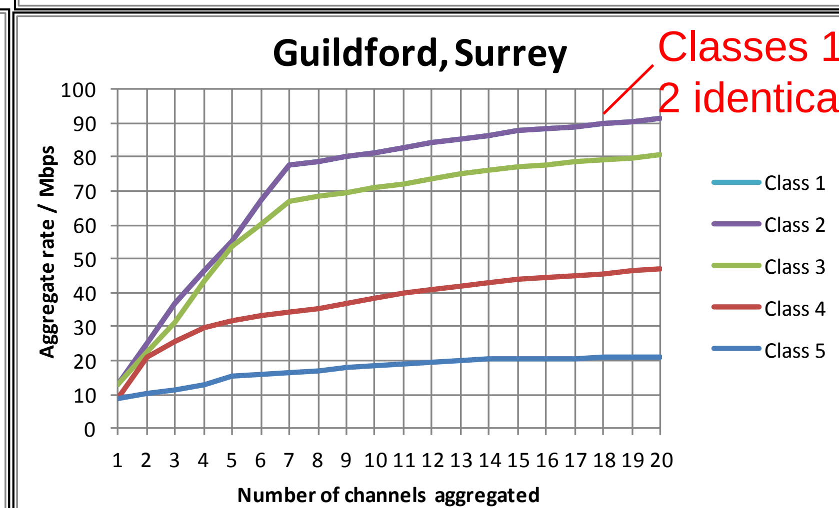


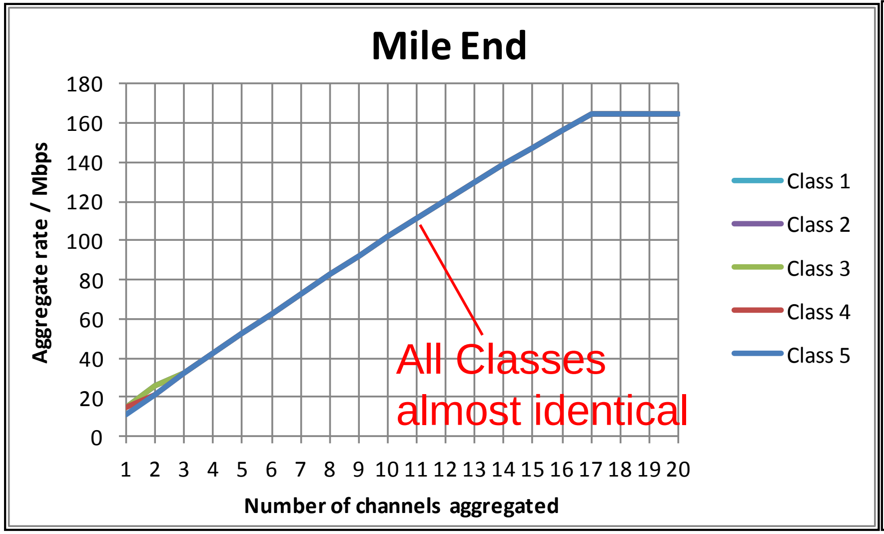


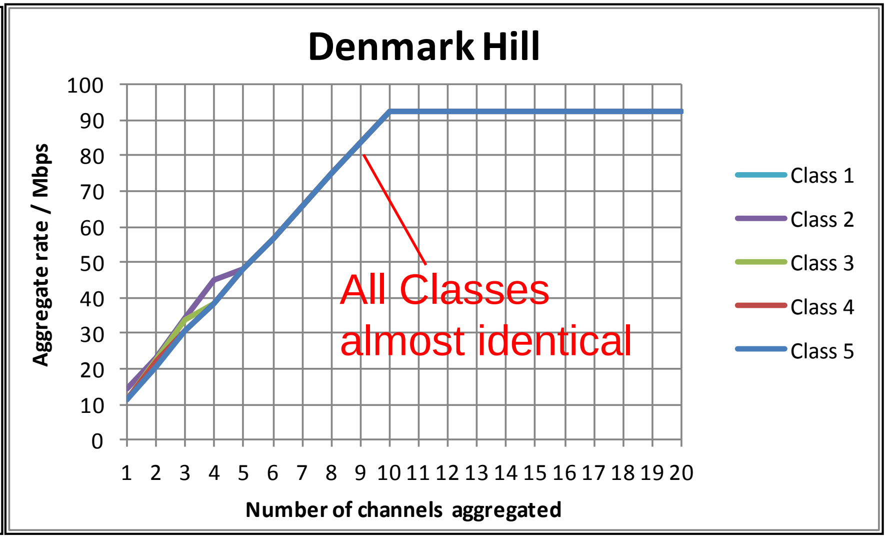


Classes 1 and 2 identical

Capacity Through Aggregation

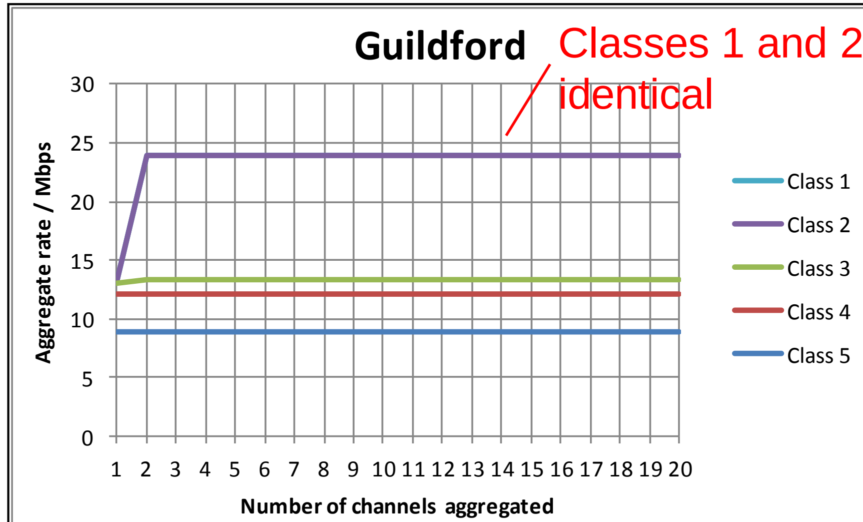
- "Mobile Broadband Downlink" scenario
  - Contiguous aggregation only (single radio covering multiple channels)
    - Rule: for all possible sets of *n* contiguous channels set power (per channel) to the lowest of those allowed for the contiguous channels, then take the result for the highest rate among the possible sets of contiguous channels with this power limitation
  - Except for rare examples (e.g., Guildford, below), Class doesn't have major effect on capacity achievable

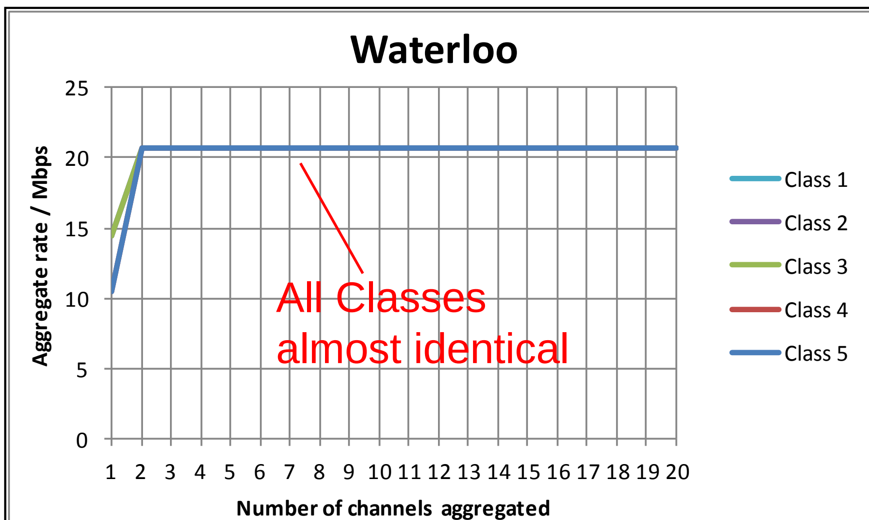


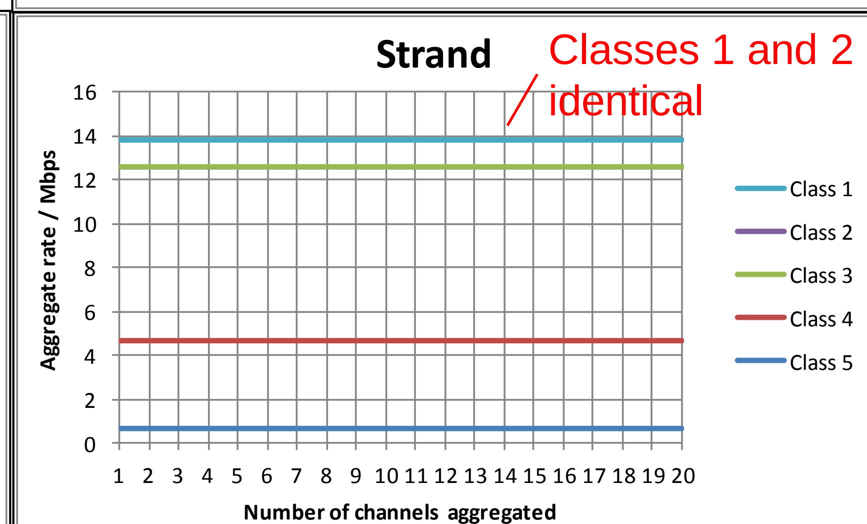


Capacity Through Aggregation

- "Mobile Broadband Downlink" scenario
  - Contiguous aggregation only (single radio covering multiple channels)
    - Same rule/observations







WRC 2015: How Much of a Problem for TV White Space?

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- ~694-790 MHz to be assigned to mobile broadband on co-primary basis – precise rules and lower bound to be decided at WRC 2015 (November 2015)
  - What happens if all goes to mobile broadband, no white space access allowed (worst case scenario)?
  - Rule out all channels above 48 (upper edge 694 MHz)
- "Mobile Broadband Downlink" scenario (>= 30 dBm for num chan)

Number of channels

	Class 1	Class 2	Class 3	Class 4	Class 5
Average	8.5	8.4	8.1	5.6	3.6
STD	5.0	5.0	5.1	4.6	3.5
CoV	0.58	0.60	0.62	0.82	0.96

Achieved Rate (Mbps)

	Class 1	Class 2	Class 3	Class 4	Class 5
Average	102.2	100.4	90.8	67.4	43.7
STD	53.0	53.4	51.5	46.3	34.0
CoV	0.52	0.53	0.57	0.69	0.78

- "Indoor Wireless Local Area Networking" scenario (>= 20 dBm for num chan)

Number of channels

	Class 1	Class 2	Class 3	Class 4	Class 5
Average	14.1	14.1	14.0	13.3	12.0
STD	2.6	2.7	2.8	3.4	4.2
CoV	0.19	0.19	0.20	0.26	0.35

Achieved Rate (Mbps)

	Class 1	Class 2	Class 3	Class 4	Class 5
Average	165.4	163.0	160.0	146.2	121.5
STD	36.8	37.6	40.3	45.2	43.4
CoV	0.22	0.23	0.25	0.31	0.36

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So, What is Achievable in TV White Space?

—Performance Testing

(far more detail in back-up slides at end of presentation)

Long-Distance Links

- KCL Denmark Hill to Queen Mary (Mile End)
  - 7km
  - Direct line of sight, although many objects in first “Fresnel Zone”
- KCL Denmark Hill to KCL Guys (London Bridge)
  - 3.7km
  - Direct line of sight, from hospital tower on Guys side so far fewer if any objects in first “Fresnel Zone”

Long-Distance Links

- Actual performance tests with Carlson devices
- Long distance (7km) Queen Mary to Denmark Hill link has been extremely challenging due to interference from distant TV transmitters, even on channels in which the devices are allowed to use maximum power. Also Fresnel effects, despite almost certain to be direct line of sight between the two sites
- E.g., channel 48 allowed to use maximum power (36 dBm EIRP) at both ends
  - Achievable SINR significantly less than zero, although unreliable measurements from the device due very low numbers
- *Far better* to use, e.g., channel 37, on which 5dB less than maximum power is allowed (31 dBm EIRP), however, interference is extremely low—likely linked to 600MHz clearout and spectrum award in the UK
  - *Far better* performance can be achieved: data rate only in the range of 20 to 60 kb/s in initial exploratory investigations, although this is *very far from optimised* currently and we expect that at least a magnitude improvement is possible; observed SINR 8-10 dB *in best case*

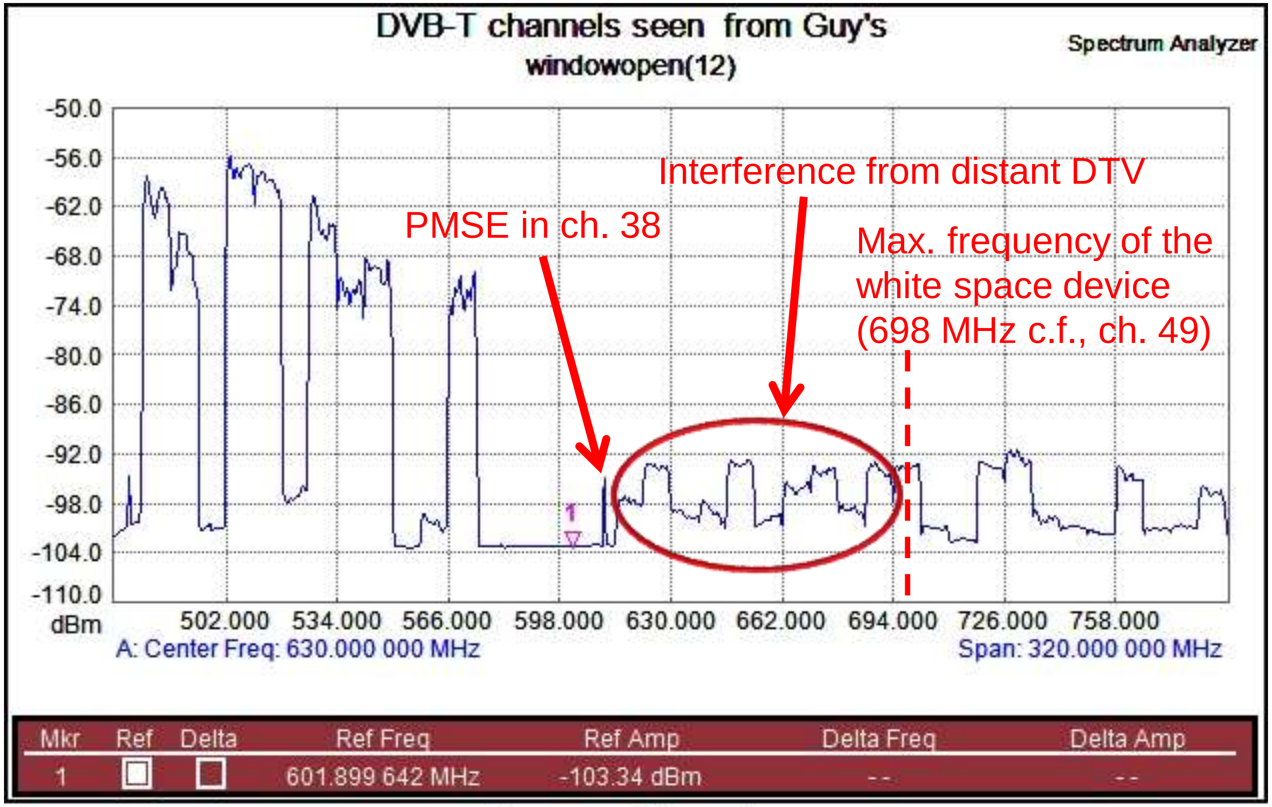
Long-Distance Links

- Approx. 3.7 km link between Denmark Hill and Guys also tested, and this is better. In the channel 37 case, up to 20 dB SINR achieved → BER ~ 10^{-6} with 16QAM modulation and coding rate 1/2 → 6.4 Mbps downlink and 5.1 Mbps uplink

- Interference (even with our vertically-polarised antennas vs. the horizontally-polarised DTV transmissions) implies that device should carefully sense channel quality/interference first before selecting channel to use. Also has implications for scenarios in which TV White Space will be most successful, and for secondary-secondary coordination and tragedy of the (spectrum) commons

- Interestingly, have found the propagation environment for these rooftop long-distance direct line-of-sight links to match closely to Hata Open path loss model

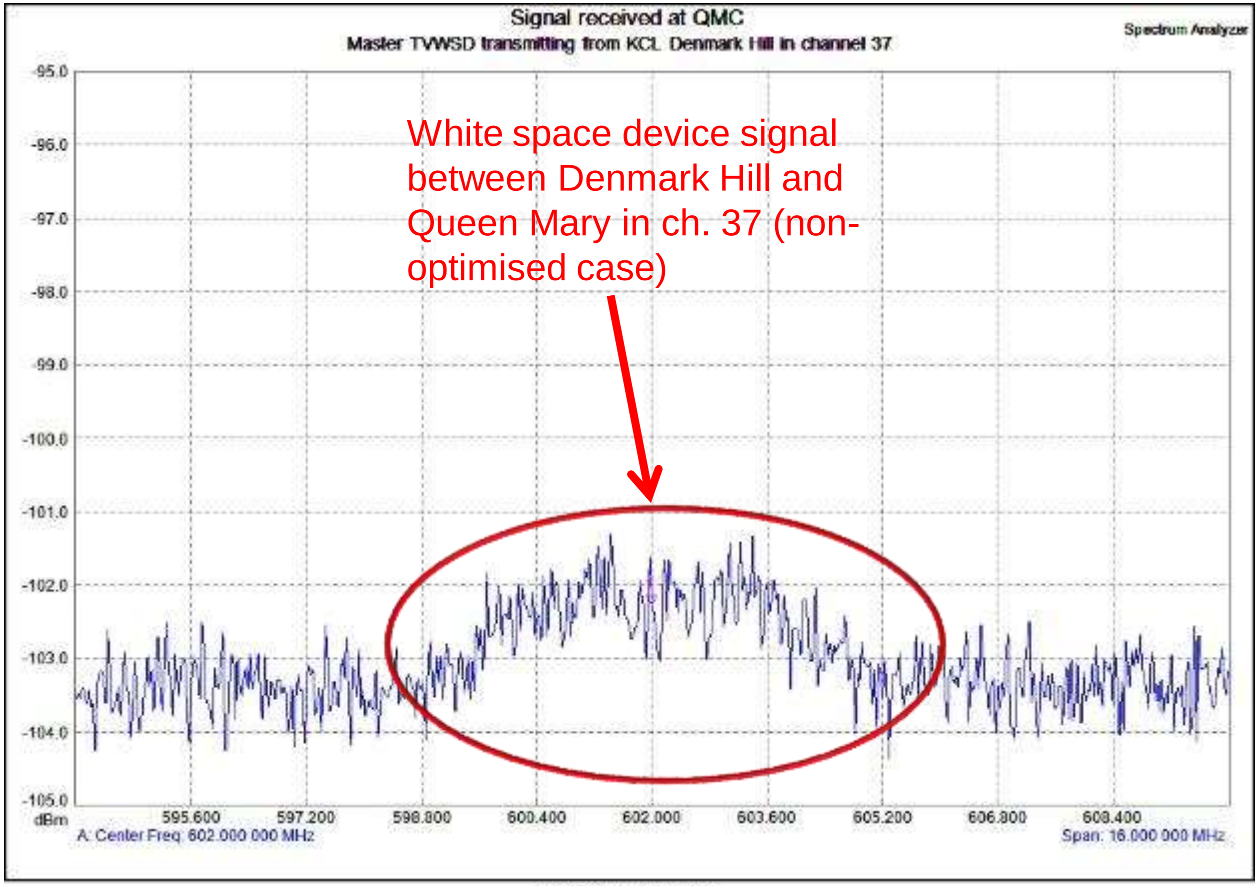
Long-Distance Links



Measurement Parameters

Trace A data:Trace Average	10	Start Frequency	470.000 000 MHz
Trace Mode	Average	Stop Frequency	790.000 000 MHz
Preamp	OFF	Frequency Span	320.000 000 MHz
Min Sweep Time	5E-05 S	Reference Level	-20.000 dBm
Reference Level Offset	0 dB	Scale	10.0 dB/div
Input Attenuation	0.0 dB	Serial Number	942140
RBW	30.0 kHz	Base Ver.	V3.08
VBW	30.0 kHz	App Ver.	V4.15
Detection	RMS	Date	8/6/2014 9:31:35 AM
Center Frequency	630.000 000 MHz	Device Name	ms2721b_01ri20090352874

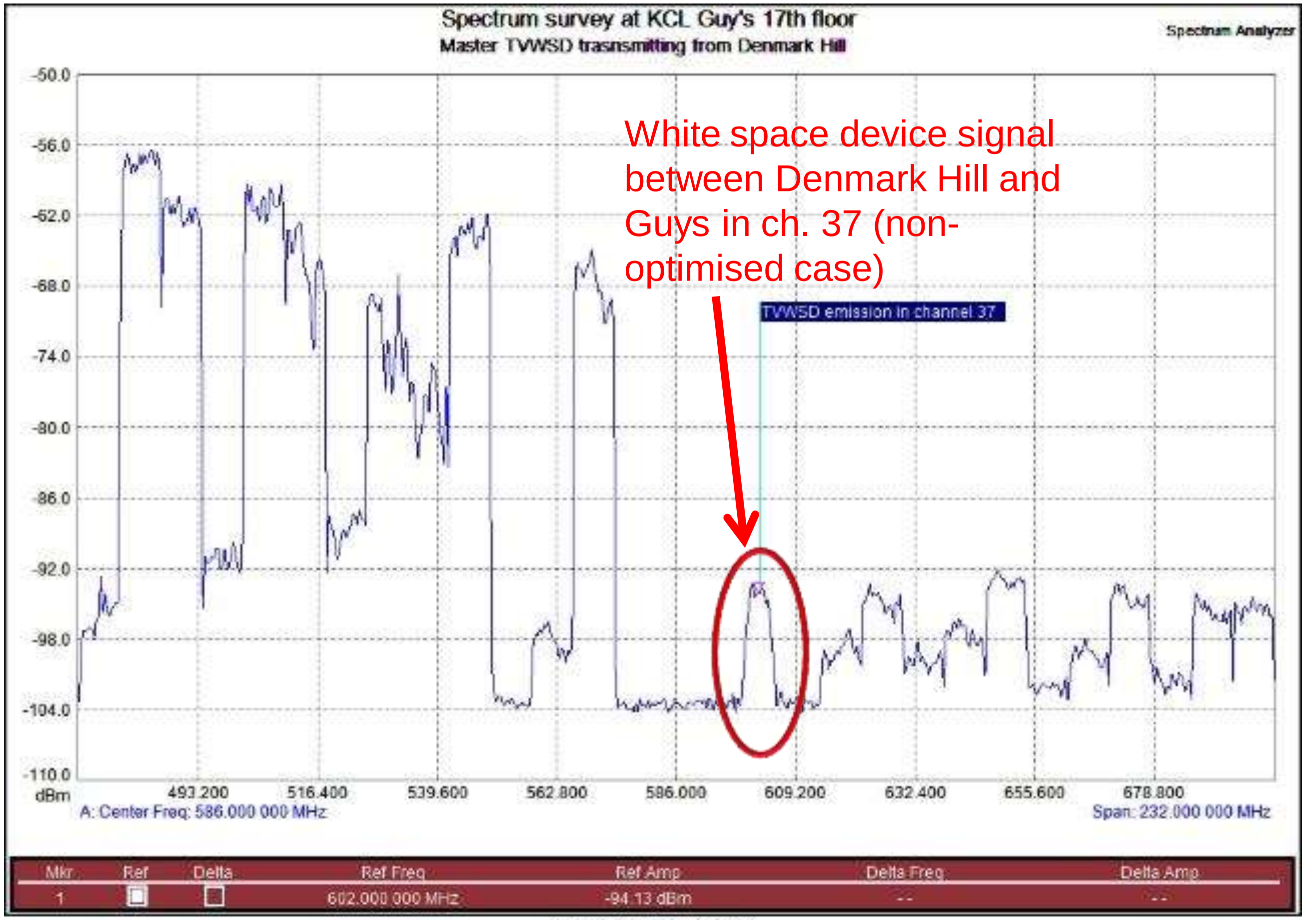
Long-Distance Links



Measurement Parameters

Trace A data:Trace Average	10	Frequency Span	16.000 000 MHz
Trace Mode	Average	Reference Level	-95.000 dBm
Preamp	OFF	Scale	1.0 dB/div
Min Sweep Time	5E-05 S	GPS Longitude	W 0 2 29
Reference Level Offset	0 dB	GPS Latitude	N 51 31 22
Input Attenuation	0.0 dB	GPS Fix Time	08 07 2014 11 02 58
RBW	30.0 kHz	Serial Number	942140
VBW	30.0 kHz	Base Ver.	V3.08
Detection	RMS	App Ver	V4.15
Center Frequency	602.000 000 MHz	Date	8/7/2014 3:39:04 AM
Start Frequency	594.000 000 MHz	Device Name	ms2721b_01r120090352874
Stop Frequency	610.000 000 MHz		

Long-Distance Links



Measurement Parameters

		Start Frequency	470.000 000 MHz
Trace Mode	Normal	Stop Frequency	702.000 000 MHz
Preamp	OFF	Frequency Span	232.000 000 MHz
Min Sweep Time	5E-05 S	Reference Level	-50.000 dBm
Reference Level Offset	0 dB	Scale	6.0 dB/div
Input Attenuation	0.0 dB	Serial Number	942140
RBW	30.0 kHz	Base Ver.	V3.08
VBW	30.0 kHz	App Ver.	V4.15
Detection	RMS	Date	8/6/2014 8:40:39 AM
Center Frequency	586.000 000 MHz	Device Name	ms2721b_01ri20090352874

Long-Distance Links—Strand to Waterloo

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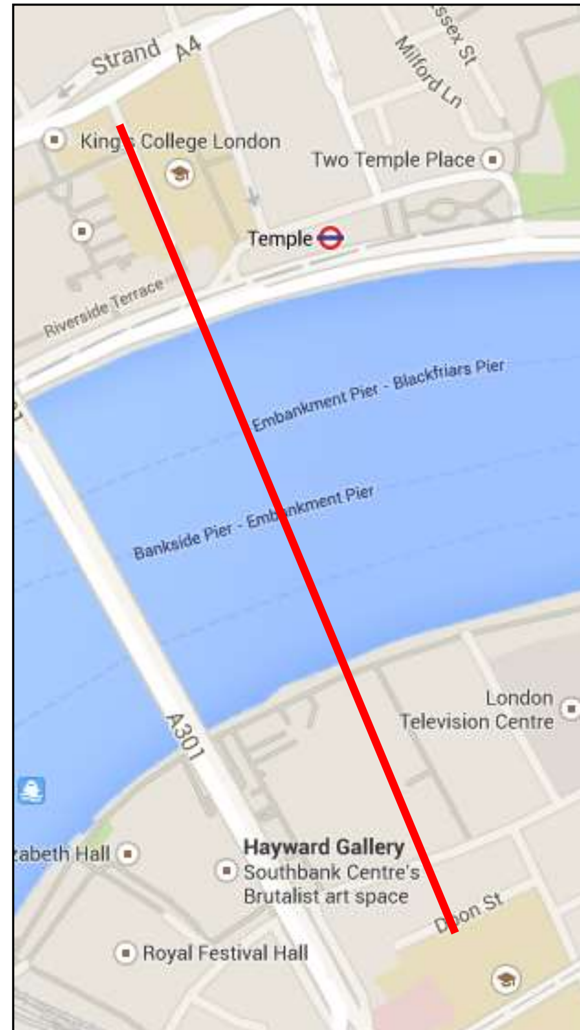
- 700m across River Thames, direct line of sight, although indoor at each end through challenging windows—not measured yet but loss through windows combined is at the *very least* 20 dB
- Database only allows to transmit at 31 dBm EIRP max at each end, using either channel 27 or 37 (the common channels at each end)
- Various speed tests using a range of tools/means: 0.1-1.7 Mbps d/l, 0.1-0.2 Mbps u/l
  - Without high-loss windows (i.e., outside), anticipate would comfortably achieve close to maximum rate for the WSDs, e.g., around 10-12 Mbps d/l, 2-3 Mbps u/l
- Noted that there was quite a big variance with even small moves of the antennas
- Noted that Strand and Waterloo are perhaps some of the most challenging locations in the whole of the UK for TV white space due to local PMSE usage (theatres, TV production, etc.)



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Long-Distance Links—Strand to Waterloo

- Examples
- 31dBm EIRP each side

3.4	-0.4	BPSK ¾	BPSK ½

0.0	0.9	BPSK ¾	BPSK ½

d/l SINR u/l SINR d/l rate u/l rate

0.5	3.2	BPSK ¾	BPSK ¾

3.6	-0.5	BPSK ½	BPSK ½

0.7	1.0	BPSK ¾	BPSK ½

Channels 27 and 37 are common

Strand, BS

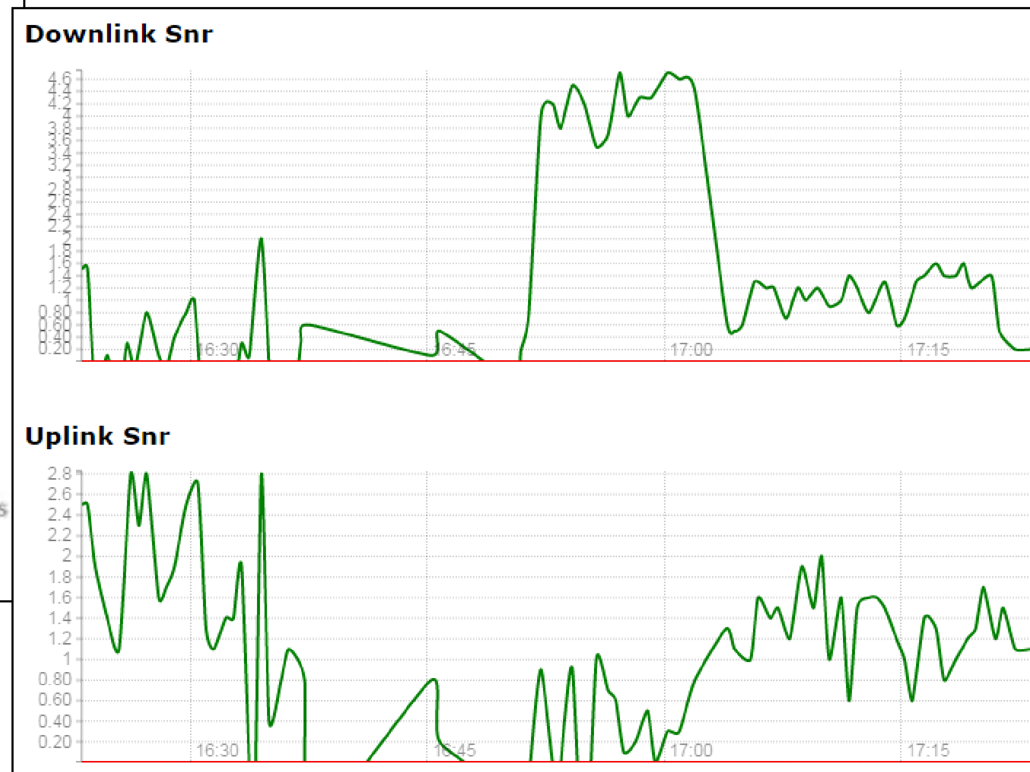
Name
ACROPOLIS Trial Base Station 1
Role
BaseStation
FccId
OPA-RC2-BS
Latitude
51.511911
Longitude
-0.11629
Antenna Height (m)
25
Notes

WSDB Access
Registration state
Registered
Status of last database access
Channels successfully retrieved
Time of last registration attempt
10/13/2014 1:38:00 PM
Channels returned on last database access
522,578,602
Time of last channel fetch
10/13/2014 5:28:00 PM

Waterloo, CPE

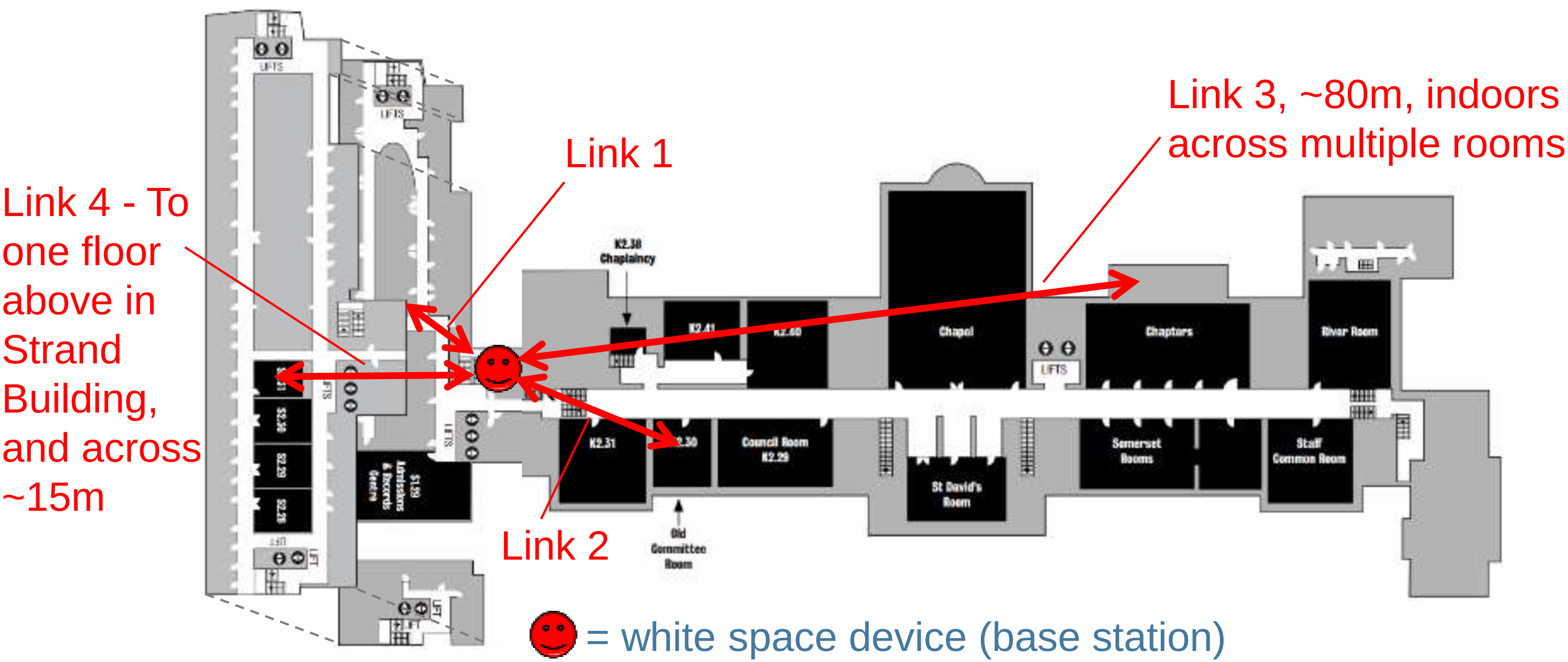
Name
ACROPOLIS Trial Terminal 2
Role
Client
FccId
OPA-RC2-CPE
Latitude
51.505905
Longitude
-0.112516
Antenna Height (m)
20
Enabled
✓
Notes
CST00801

WSDB Access
Registration state
Registered
Status of last database access
Channels successfully retrieved
Time of last registration attempt
10/13/2014 1:39:00 PM
Channels returned on last database access
498,522,602,674,682
Time of last channel fetch
10/13/2014 5:29:00 PM



Indoor Strand

- Early tests at the Strand Campus of King’s College London
- There is no channel at which maximum power can be used, although two channels in which 31 dBm (5 dB below maximum) can be used



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Indoor Strand

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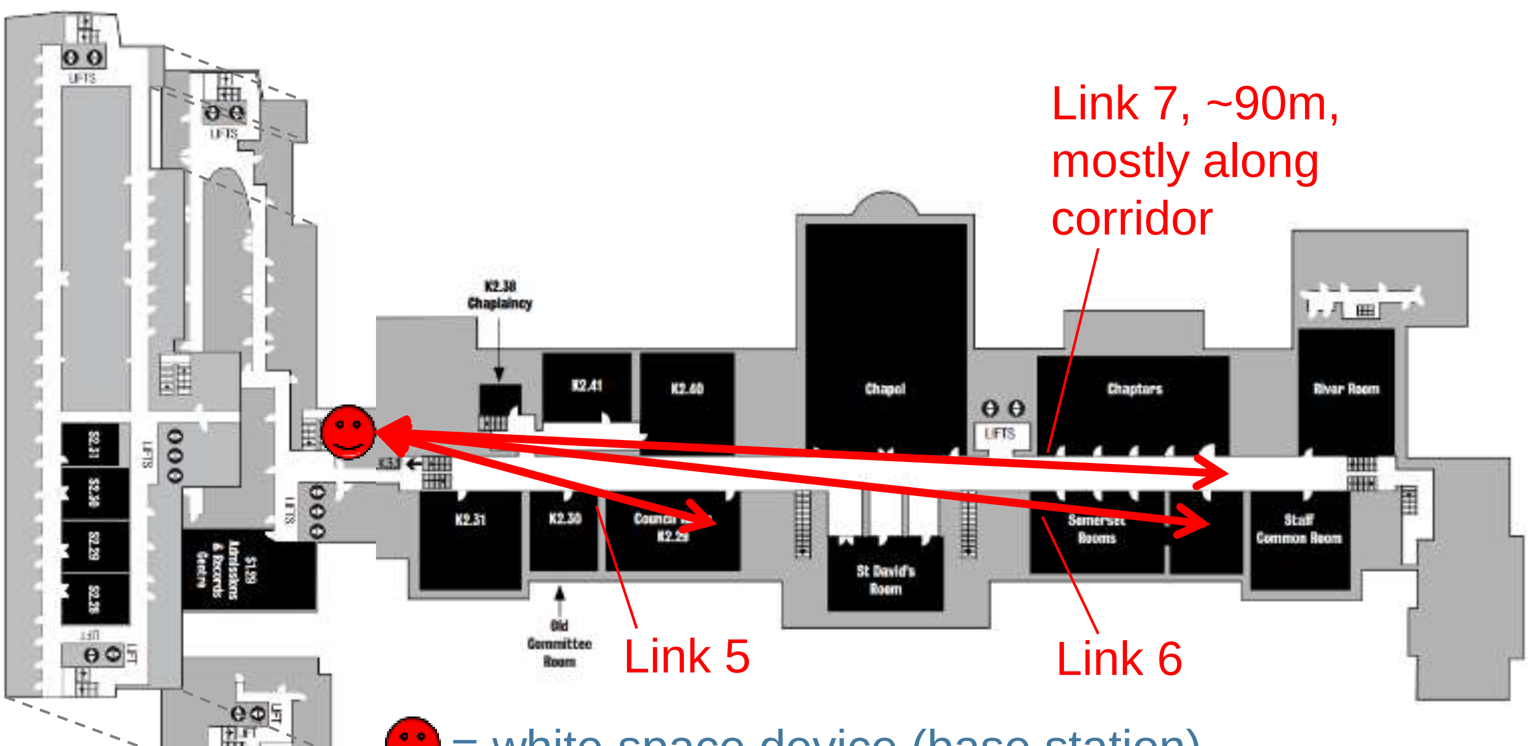
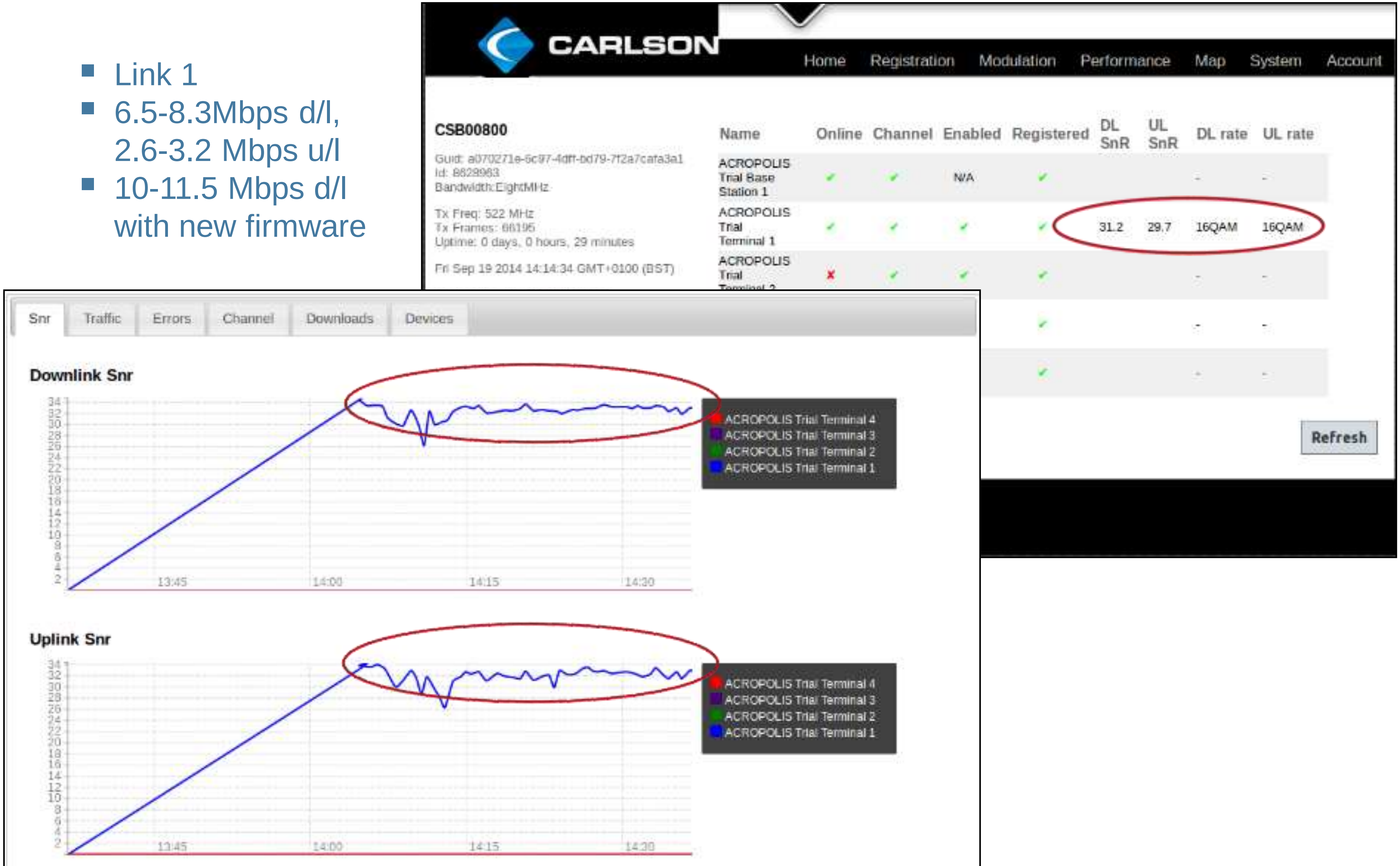


= white space device (base station)

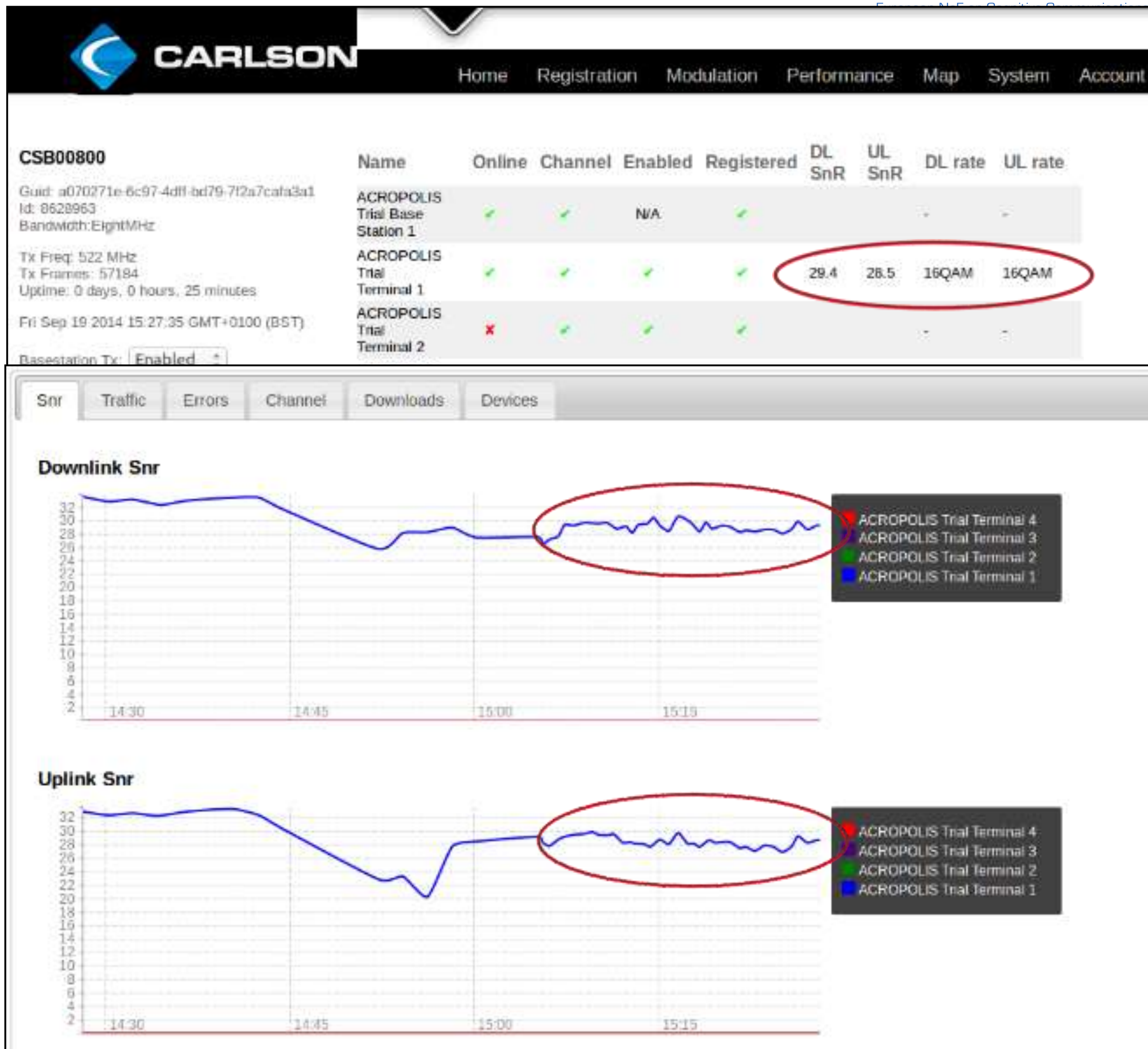
Indoor Strand

- Link 1
- 6.5-8.3Mbps d/l, 2.6-3.2 Mbps u/l
- 10-11.5 Mbps d/l with new firmware



Indoor Strand

- Link 2 (to Old Committee Room)
- 5.7-9.9 Mbps d/l; 1.0-2.2 Mbps u/l
- 100MB download test, 138 seconds → 5.8 Mbps average
- Note, latter was after the link dropped to a lower modulation/coding rate



Indoor Strand

- Link 3 (to Refectory)
- 1.1-9.8 Mbps d/l; 0.1-1.2 Mbps u/l
- 20MB download test, 131 seconds → 1.2 Mbps
- Variance is due to testing extremely good as well as more average antenna positions; lower achieved rates are for average antenna position

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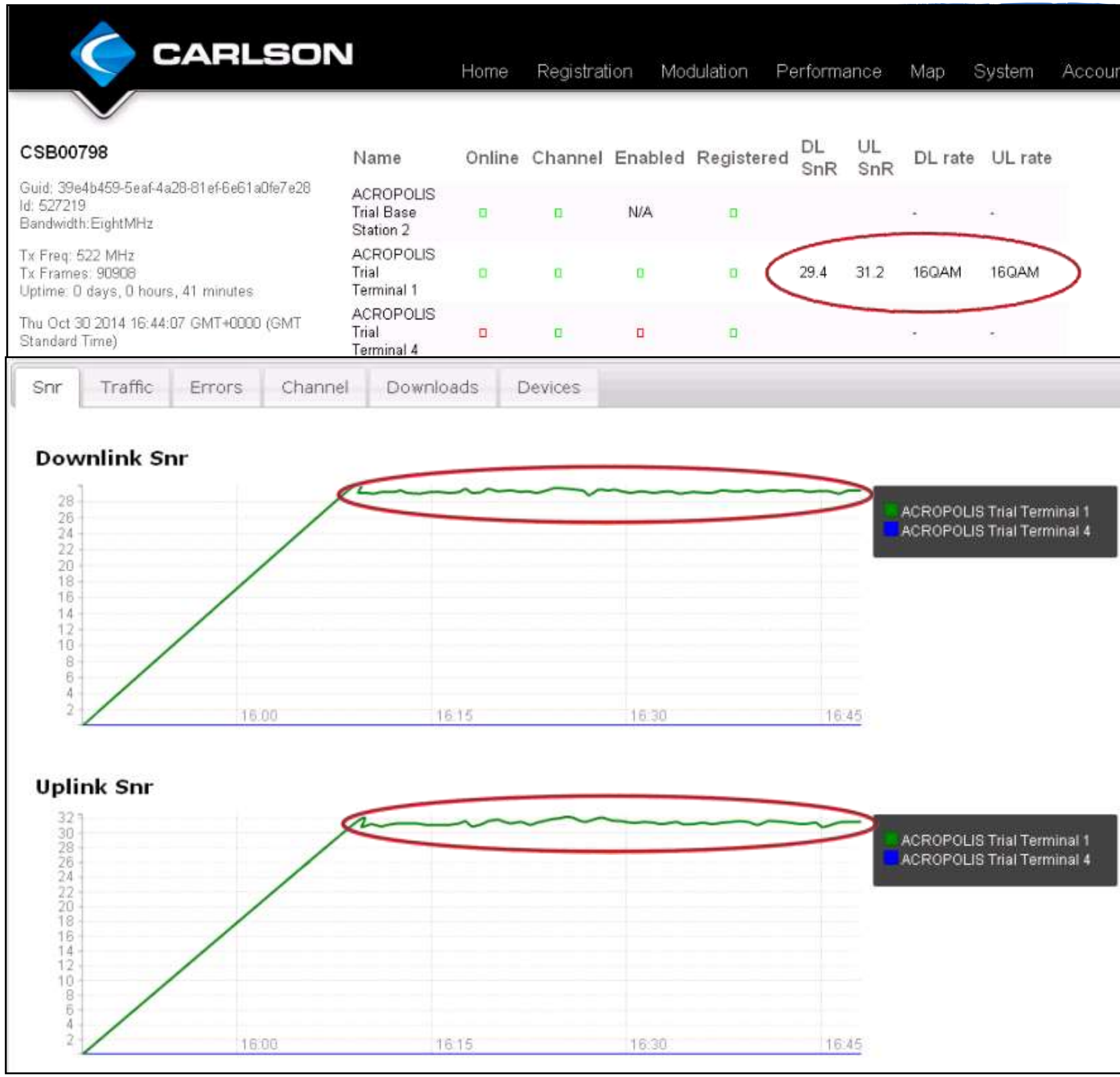
Indoor Strand

- Link 4 (to floor above and ~10m across in Strand, passing through several rooms)
- This time using the new firmware; also tested using a range of tools
- 10.9-11.6 Mbps d/l; 1.7-2.3 Mbps u/l
- 50MB download test, 40 seconds → 10 Mbps



Indoor Strand

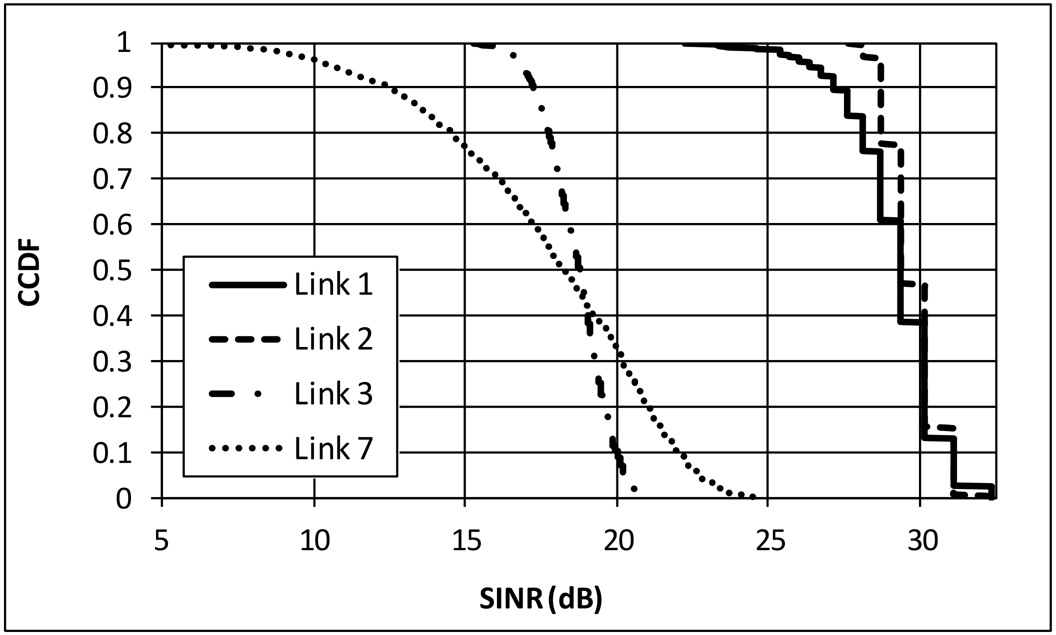
- Link 5
  - In range of 3.3-9.1 Mbps d/l; 1.1-2.5 Mbps u/l
  - 16 QAM no coding BER ~10^{-3}, adding Conv 75 coding already makes BER better than around ~10^{-5}

- Link 6
  - Very challenging scenario as is approx 90m also on opposite side of the building
  - Have to use lowest modulation and highest coding (BPSK, Conv 50)
  - Still can only achieve around BER of in range of 10^{-2} to 10^{-3}
  - Such values consistent with very low throughput, although throughput not yet measured throughput for this scenario

- Link 7
  - Typically requires at least reduction to QPSK with Conv 50 coding in order to achieve usable link (BER typically 10^{-4} or better)
  - Throughput not use measured yet in this scenario, although values consistent with rate of small number of Mbps (e.g., 2-4 Mbps)
  - Also tested with other WSD, base station moved to corridor directly outside lab; achieved 6Mbps throughput along almost the entire length of KCL Strand/King's

Indoor Strand

- Achieved SINR distributions (CCDFs) for some of the links
  - Noted that white space equipment returns only particular values of SINR for some higher values—hence blocky looking effect on rightmost plots
  - Very high variance for Link 7 due to different numbers of people in corridor
  - Some variance for Link 1 due to people in vicinity of antennas, and opening/closing door to room
  - Other links relatively stable



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DTT Coexistence

- Created challenging scenarios for interfering with DTT
- DTT monitored by Wavecom Wavesys system
  - Also allows the recording of “transport streams” to see the effects on actual stream, as well as obtaining some various statistics
- Wavesys listening to DTT on Channel 25 or Channel 23
- White space device transmitting on adjacent Channel 24, at maximum allowed power of 33 dBm EIRP for that adjacent channel
- DTV reception antenna and white space transmission antenna mounted on the same pole, some 15cm apart from each other

DTT Coexistence

- No noticeable effect on the DTT transport stream

  Without white space device transmitting, DTT on channel 25:

  ts 0 33 20.vlan

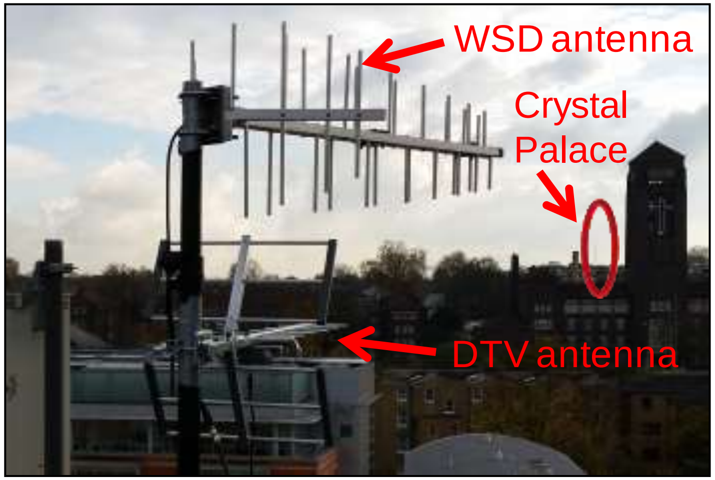
  With white space device also transmitting on channel 24:

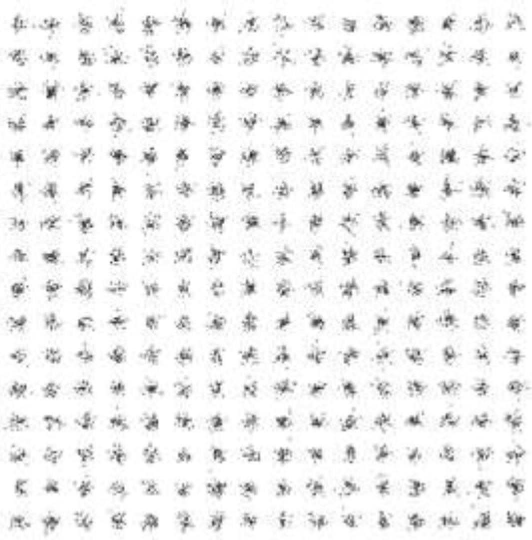
  ts 0 39 26.vlan

- Also various statistics are available and being investigated for these cases

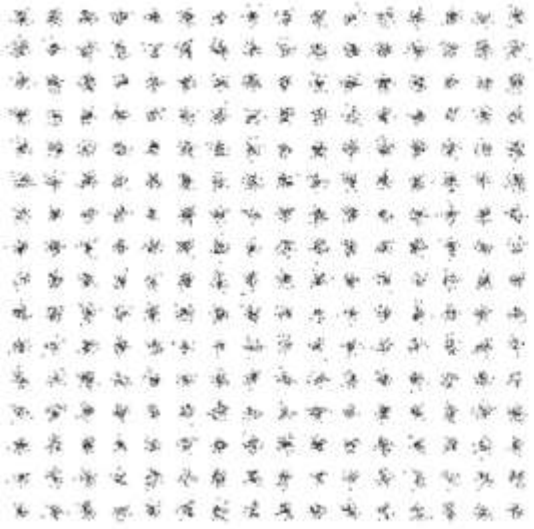
DTT Coexistence

- Constellation—no statistical difference between DTT constellations with, and without, white space device transmitting
  - Challenging case as reflected on right, approx co-linear to maximise coupling
  - 256-QAM (!) DTT, white space device on adjacent channel, max allowed power





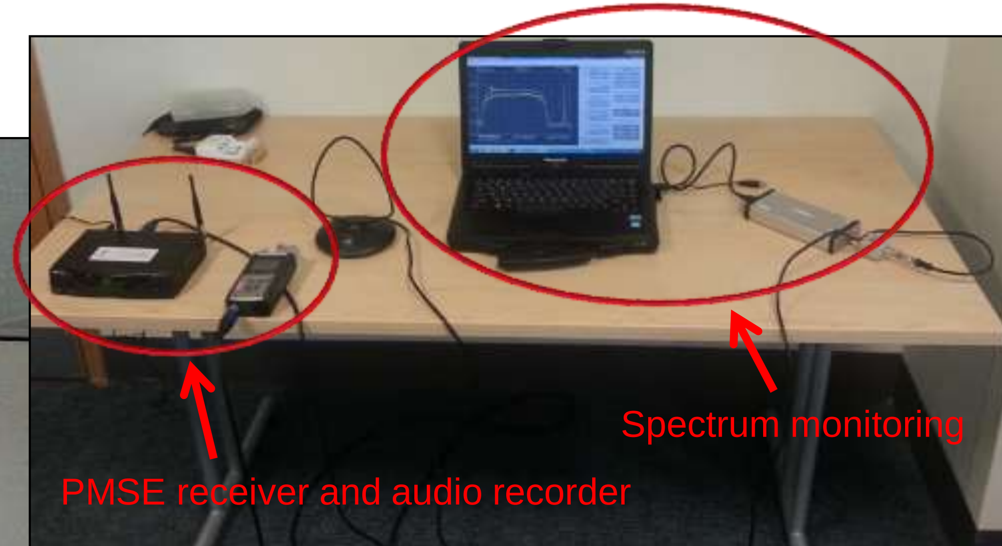
Without white space device transmitting



With white space device transmitting

PMSE Coexistence

- PMSE interference scenario



PMSE Coexistence

- No noticeable interference effects based on PMSE listening tests
- Will be expanded to large scale blind listenings and multiple choice questions of the recordings among a large number of students, and statistical analysis of the blind listening tests
- An example (note, limiting factor in this presentation is likely the audio on my laptop and/or the audio system in the conference room…!)

  Without white space device transmitting: MONO-019.wav

  With white space device transmitting: MONO-027.wav

  For comparison, what interference (white space device on same channel as PMSE) sounds like: STE-037.wav
- Note, a video that is not in the public domain has been made explaining what was done – please ask me if you want access to it

Conclusion

Conclusion

- Given high-level overview of TV white spaces in the UK
- Described aspects of our trial
- Overviewed performances that are possible in TV white spaces in terms of availability (number of channels) and capacity (including aggregation of channels)
  - Mobile broadband downlink
  - Indoor wireless local area networking
  - Non-contiguous aggregation
  - Contiguous aggregation
  - Worst case effects of WRC 2015 on availability and performance of TV white spaces
- Described some of the experimental results so far

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Conclusion - Observations

- Key observation is that interference exists (at least in London) in above-rooftop receiver scenarios
  - “Mobile Broadband Downlink” and “Indoor Wireless Local Area Networking” scenarios defined/investigated for availability/capacity studies based on that
  - Long-distance links, wide-area broadband, etc., challenging due to interference, at least in UK case
  - High max EIRP (36 dBm) and good propagation will make above-rooftop interference worse when interactions among white space devices considered
  - Very good propagation suited to the indoor cases
- There is ample TVWS in the UK, and conversely to expectations, excellent TVWS in London due to shadowing effects reducing interference to primary receivers, and “tidy” coverage by a single TV transmitter (not “blocking” multiple set of channels), etc.
- In a number of cases, especially under aggregation, spectrum mask chasses achieve similar performance (e.g., Classes 1-3). Particularly case under contiguous aggregation
- WRC 2015 (especially worst-case outcome) is not good for TVWS
- Ofcom framework needs updating—“generic slave” parameters approach is impractical as powers too low (they are working on a solution to that)

Acknowledgements – Key People (participants or collaborators)

- Led by
  - Oliver Holland – King's College London, UK (overall manager/leader)
  - Pravir Chawdhry – Joint Research Centre of the European Commission, EU/Italy
  - Raymond Knopp – Eurecom, France

- Some other key people (may not be exhaustive)
  - Shuyu Ping, Nishanth Sastry, Hong Xing , Adnan Aijaz, Suleyman Taskafa – King's College London, UK
  - Jean-Marc Chareau, James Bishop, Michele Bavaro, Tiziano Pinato, Philippe Viaud, Emanuele Anguili – Joint Research Centre of the European Commission, EU/Italy
  - Reza Akhavan – Imperial College London, UK
  - Florian Kaltenberger, Dominique Nussbaum – Eurecom, France
  - Juhani Hallio, Mikko Jakobsson, Jani Auranen, Reijo Ekman, Jarkko Paavola, Arto Kivinen – Turku University of Applied Sciences, Finland
  - Yue Gao, Zhijin Qin, Qianyun Zhang – Queen Mary University of London, UK
  - Ha-Nguyen Tran, Kentaro Ishizu, Takeshi Matsumura, Kazuo Ibuka, Hiroshi Harada – NICT, Japan
  - Rogerio Dionisio, Jose Ribeiro, Paulo Marques – Institute of Telecommunications, Portugal
  - Keiichi Mizutani – Kyoto University, Japan
  - Heikki Kokkinen, Olli Luukkonen – Fairspectrum, Finland
  - Tomaž Šolc, Mihael Mohorčič – Jožef Stefan Institute, Slovenia
  - David Grace – University of York, UK
  - Klaus Moessner – University of Surrey, UK
  - David Crawford – University of Strathclyde, UK
  - Andrew Stirling – Larkhill Consulting, UK

Key People Who have Participated in Getting Early Results So Far

- Oliver Holland, Shuyu Ping, Nishanth Sastry, Hong Xing, Adnan Aijaz, Suleyman Taskafa – King's College London, UK
- Pravir Chawdhry, Jean-Marc Chareau, James Bishop, Michele Bavaro, Tiziano Pinato, Philippe Viaud – Joint Research Centre of the European Commission, EU
- Frank Gao, Zhijin Qin, Qianyun Zhang – Queen Mary University of London, UK
- Paulo Marques, Rogerio Dionisio, Jose Carlos Ribeiro – Institute of Telecommunications, Portugal
- Reza Akhavan – Imperial College London, UK
- Heikki Kokkinen – Fairspectrum, Finland
- Numerous NICT collaobrators (see next presentation)

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Acknowledgements – Key Projects

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Thank you!
Questions/discussion?

Oliver Holland
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Glasgow, UK, 14 May 2015

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Back-up Slides

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Ofcom/ETSI Framework: White Spaces in the UK

Device Types

- Master
  - Geolocated; able to communicate directly with a geolocation database
- Slave
  - Only able to communicate with other white space devices; under the control of a master device; not necessarily geolocated
- Type A
  - Fixed use only. Integral, dedicated or external antennas
- Type B
  - Not intended for fixed use. Integral or dedicated antenna

Database Discovery

- Send the following to Ofcom: https://TVWS-Databases.ofcom.org.uk/weblist.xml?UniqueID=myDeviceSerialNumber
- Response


```
▼<ws_databases xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xsi:noNamespaceSchemaLocation="https://TVWS-Dat
   <last_update>2014-10-20T13:34:00</last_update>
   <refresh_rate>1440</refresh_rate>
 ▼<db>
     <url>https://tvwsdb.broadbandappstestbed.com/json.rpc</url>
     <db_provider_name>Spectrum Bridge Incorporated</db_provider_name>
     <ws_db_id>1</ws_db_id>
   </db>
 ▼<db>
     <url>https://tvwsdb-ofcom.nict.go.jp:4433/</url>
     <db_provider_name>NICT</db_provider_name>
     <ws_db_id>2</ws_db_id>
   </db>
 ▼<db>
     <url>https://www.fswsdb.com/wsd/index.php</url>
     <db_provider_name>Fairspectrum</db_provider_name>
     <ws_db_id>3</ws_db_id>
   </db>
```


…

- Check again every refresh_rate minutes—currently 1,440 mins, 24 hours. If can’t be accessed then check again every 1-2 hours, and continue using the last received information

Device-Database Communications

- Typically close to IETF Protocol for White Space Access (PAWS), https://datatracker.ietf.org/doc/draft-ietf-paws-protocol, **although this is not a requirement so there are (sometimes considerable) differences in device-database communication implementations for the UK case**
  - Leads to pairings of manufacturers/databases; firmware and/or other updates typically necessary if device wishes to change to a different database→databases are typically **not** interchangeable
- Typically (in fact, for all the implementations we have seen) JSON messages
- Devices must check with database at start-up before transmitting and every 15 minutes; if any check fails then they must immediately stop transmitting
- Following order – note, I use my own terminology to describe the phases
  - Master specific messages
  - Master usage messages
  - Slave generic messages
  - Slave specific messages
  - Slave usage messages

Master Specific Messages

- Process can start only after the master has checked and selected a database from the Ofcom list of gelocation databases
- Master obtains specific parameters from one of those databases for itself
  - Sends its information to the database, including its description (manufacturer, model, serial number, type (A or B), master or slave, spectrum mask class of performance (although this is sometimes substituted simply for the serial number, under the assumption that the database knows the device characteristics based on the serial number), technology identifier), location (including height AGL—optionally with other information antenna orientation), among other information
  - Database calculates the powers that can be used in which channels at which times based on this information
  - Database responds with information on allowed maximum powers in which channels (database implementations vary: can be per 8MHz and power spectral density (per 100 kHz); some databases report only the density) along with other information such as a time stamp and echoed device information. Channels powers are typically in the form of a schedule, stating the start and finish times for which the information is valid

Master Usage Messages

- Master must confirm with the database which channels/powers it has chosen to use before it uses them
  - Master device responds to the database confirming again its description, location, and its chosen channels and powers. It is noted that various combinations of channels and powers can be used through the format of the associated JSON messages. Further, aggregation of channels is possible trough the information structures supported
  - Database then responds with a confirmation, or otherwise error message – if there is an error then the master must not transmit

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Slave Generic Messages

- Slave generic operational parameters reflect the worst case slave power allowed in any location that is in the master's coverage, thereby applying to a slave for which its position (among other characteristics) is not known
- Purpose is generally only to allow initial slave transmissions in link formation, although can be used on a longer-term basis if desired
  - The master requests information for a generic slave device from the database
  - The database then uses its knowledge of the master obtained in previous phases (e.g., its chosen channels/powers), among other characteristics, and also other knowledge, e.g., on location characteristics, to calculate the master's coverage. In each channel, it will take the most conservative (lowest) value of allowed slave power for any possible slave location in the master's coverage area
  - The resulting list of channels and allowed maximum powers will be returned back to the master much as for the master specific messages
  - The master can then transmit these parameters to the slave in the channel it has chosen, and the slave can start transmitting with these parameters in order to form the link and report its precise information to the master

Slave Specific Messages (Includes Master Association)

- Using the generic parameters, the slave can now transmit to the master its detail, e.g., location
- It is a requirement that the slave must anyway associate with the master, and that association must be informed to the database, whether it not the slave chooses to use the generic or specific operational parameters
  - Master sends description for itself and the slave in a message (thereby informing of the association) to the database, including now the slave’s location if specific operational parameters are required
  - The database then calculates and returns the specific allowed channels/powers for the slave’s characteristics and location
  - The master can then transmit those specific parameters to the slave on its chosen channel

Slave Usage Messages

- Slave must confirm with the database which specific channels/powers it has chosen to use before it uses them
  - Slave device responds (transmitting via the master with its generic parameters, noting that the master is the only gateway to the Internet it has) to the database confirming again its description, location, and its chosen channels and powers. It is noted that various combinations of channels and powers can be used through the structure of the associated JSON messages. Further, aggregation of channels is possible trough the information structures supported
  - Database then responds with a confirmation, or otherwise error message – if there is an error then the slave must not transmit. These messages are again relayed by the master to the slave
  - After it receives a successful confirmation, the slave can then transmit with its chosen specific parameters

Emissions Requirements—Out of TV Bands

- Quite strict requirements for out of TV band emissions by TV white space devices. However, of course can be relatively easily dealt with by fixed filters

- E.g., -54 dBm is equivalent to a class 1 white space device transmitting at no more than 20 dBm in adjacent channel – biggest challenge seems likely to therefore be satisfying the limit for LTE 800 (790-862 MHz) just above the TV band

Frequency Range	Maximum power	Measurement Bandwidth
30 MHz to 47 MHz	-36 dBm	100 kHz
47 MHz to 74 MHz	-54 dBm	100 kHz
74 MHz to 87,5 MHz	-36 dBm	100 kHz
87,5 MHz to 118 MHz	-54 dBm	100 kHz
118 MHz to 174 MHz	-36 dBm	100 kHz
174 MHz to 230 MHz	-54 dBm	100 kHz
230 MHz to 470 MHz	-36 dBm	100 kHz
790 MHz to 862 MHz	-54 dBm	100 kHz
862 MHz to 1 GHz	-36 dBm	100 kHz
1 GHz to 4 GHz	-30 dBm	1 MHz

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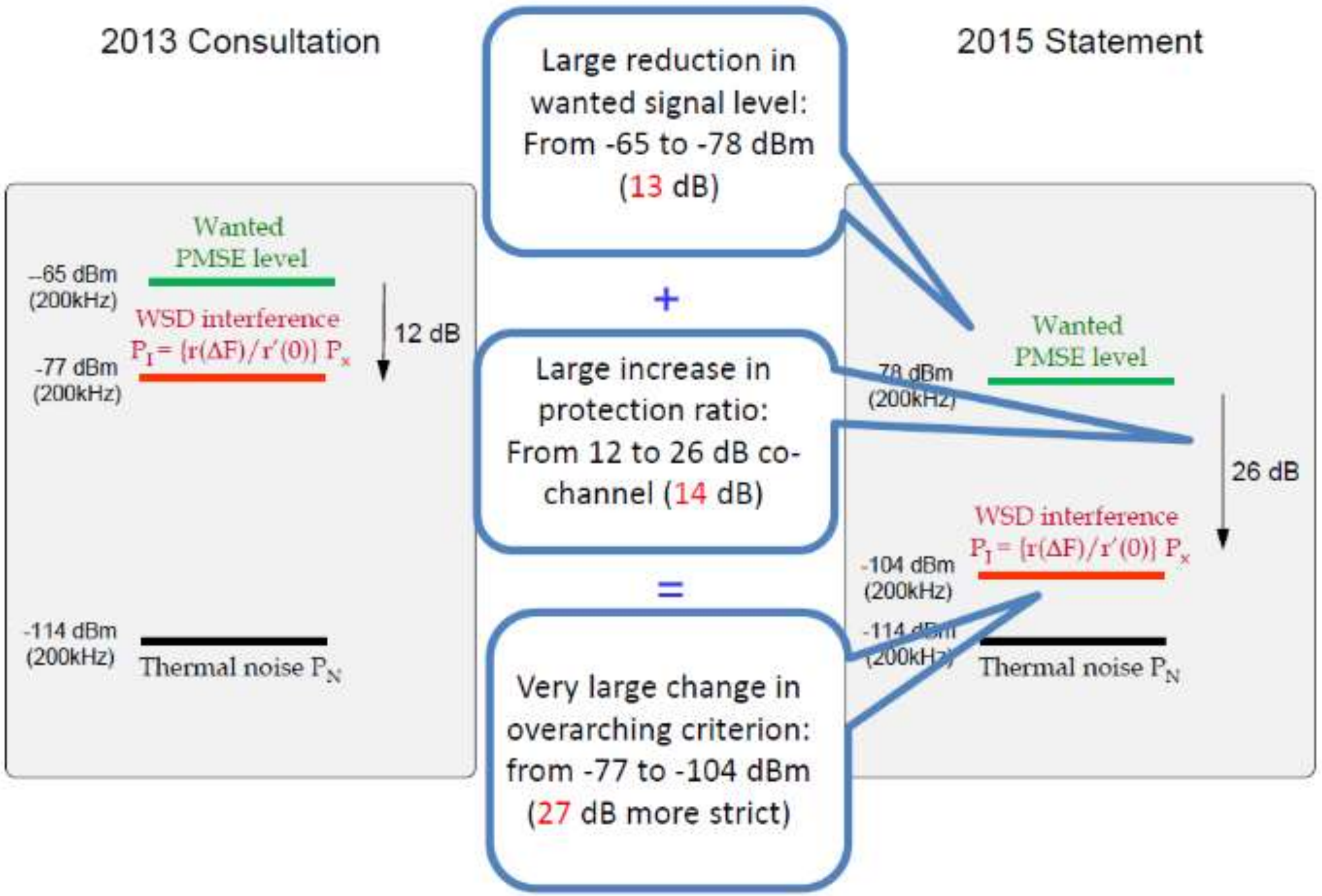
Ofcom Statement—Key Changes to the Ofcom Framework

(more detail in back-up slides at end of presentation)

Ofcom Statement—Key Changes to the Ofcom Framework

- PMSE protection (Ofcom PMSE Technical Working Group Meeting, 26 February—Copyright Ofcom)



Ofcom Statement—Key Changes to the Ofcom Framework

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- PMSE protection, Channel 38, Situation **before** statement (Ofcom PMSE Technical Working Group Meeting, 26 February—Copyright Ofcom)

2013 Consultation

Channels

Power in dBm/8MHz (maximum 36)

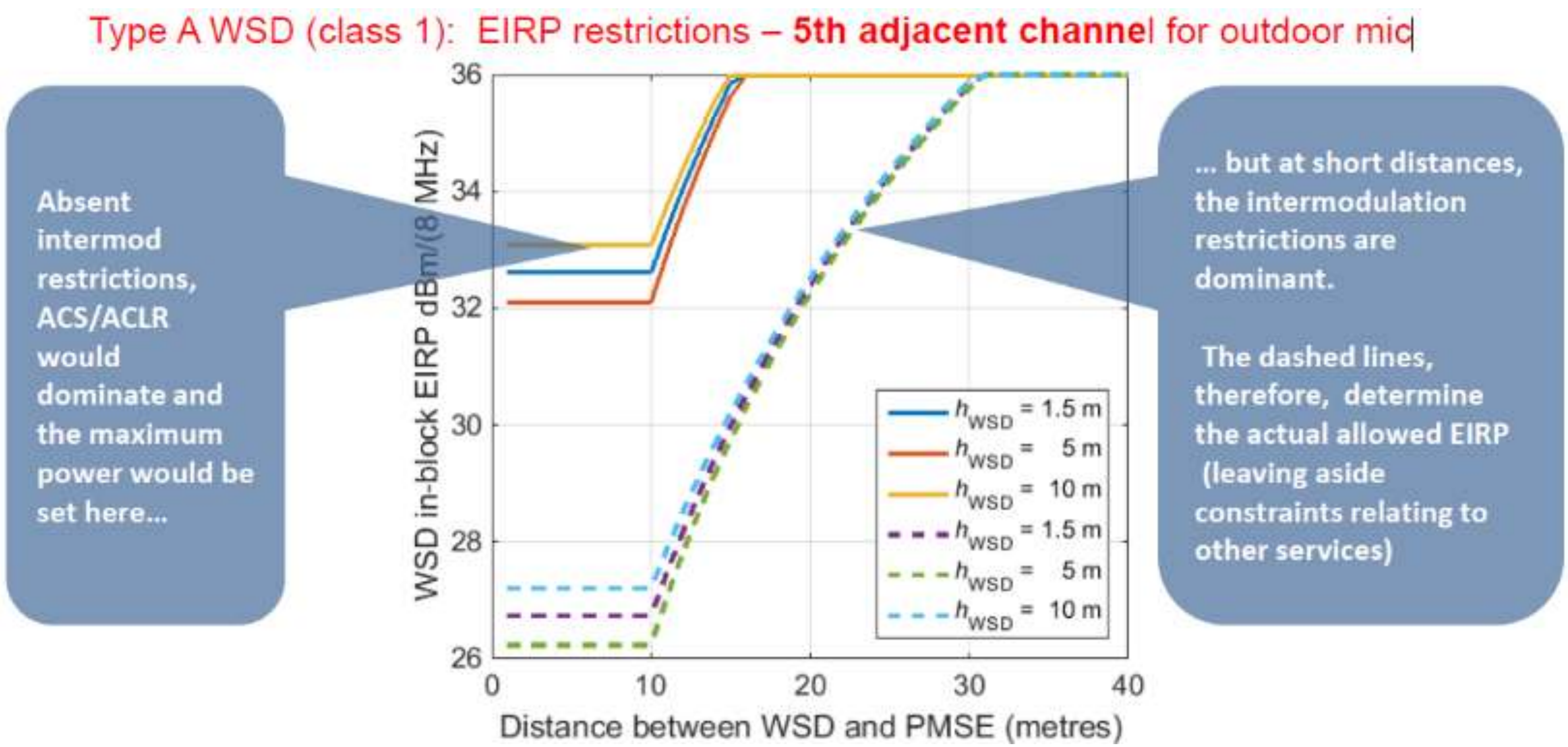
	34	35	36	37	38	39	40	41	42
Class 1	36	36	36	35		35	36	36	36
Class 2	36	36	36	35		35	36	36	36
Class 3	36	36	36	31		31	36	36	36
Class 4	36	36	32	22		22	32	36	36
Class 5	36	32	21	11		11	21	32	36

Ofcom Statement—Key Changes to the Ofcom Framework

- PMSE protection, Channel 38, situation **after** statement (Ofcom PMSE Technical Working Group Meeting, 26 February—Copyright Ofcom)

Ofcom Statement—Key Changes to the Ofcom Framework

- PMSE protection, Intermodulation (Ofcom PMSE Technical Working Group Meeting, 26 February—Copyright Ofcom)
  - Detail in Annex 4
  - Dashed lines show example intermodulation restrictions for various heights
  - Solid lines show the restrictions due to adjacent channel leakage and selectivity. The dominant restriction will depend on frequency separation



Ofcom Statement—Key Changes to the Ofcom Framework

- DTT protection
  - Changed coupling gains for tier 0/1/2 pixels from 70th percentile values to 90th percentile values. For tier 3 pixels and beyond no change
  - Used same tier 0/1 coupling gains for rural, suburban and urban pixels and not the previous lower bounds to separation distances for the different clutter classes
  - No change to approach to modelling coupling gains over longer distances based on the extended Hata model, although will keep under review
  - Recalculated protection ratio tables based on laboratory measurements with a WSD and 50 DTT receivers
  - Moved from high/medium/low classification to a high/low classification based on real time discontinuous behaviours of different WSDs
    - Proposed that further work should be undertaken to address how devices would be classified as high or low in category
  - Introduced additional margin of 9 dB to allow for DTT field strength prediction uncertainty and other real world effects for co-channel operation
  - Localised additional protection for some areas that have unusual propagation performance
  - Various other minor changes

Ofcom Statement—Further Work Potentially Resulting in Changes

- Identified due to the Pilot and Ofcom's Coexistence testing (text directly from Ofcom Statement)
  - a) Choice of propagation model in calculations to define coexistence parameters with DTT. This would include a review of the use of the extended Hata model, the assumption of 0 dB standard deviation for longer path distances, the use of Infoterra clutter data and potentially other more sophisticated terrain-based prediction models. It could also include a review of current modelling of household installation gains
  - b) Choice of propagation model in calculations to define a master WSD coverage area and coexistence parameters with PMSE. This would include a review of the use of the extended Hata model, our approach to clutter data and consideration of the use of more sophisticated terrain-based prediction models
  - c) UK DTT Planning Model data that is used in the DTT coexistence calculations – ensuring that the underlying data in the model better reflects the actual position regarding DTT viewers' reception in any particular pixel for example in terms of the transmitters that provide TV services to the viewer and the DTT field strength. This could also include a review of whether the definition of the threshold of coverage (99% time, 70% locations) reflects actual transmitter usage in weak signal areas

Ofcom Statement—Further Work Potentially Resulting in Changes

- Identified due to the Pilot and Ofcom's Coexistence testing (text directly from Ofcom Statement)
  - d) Categories of protection ratios for DTT – consideration of whether different device technologies or use cases may be more likely to disrupt DTT receivers and whether and how the framework should take account of this
  - e) Pixel resolution in the calculation limits to protect DTT services in neighbouring countries
  - f) Whether narrowband WSDs, when not in the vicinity of PMSE users, may be allowed additional power to recognise the fact that they do not use the entire 8 MHz channel and therefore their total power in the channel is lower than a comparable wideband device
  - g) Further consideration of whether there are genuine likely worst case scenarios for PMSE use that are not foreseen by the framework and where further information would help us to better understand and take account of the issues
  - h) WSD to WSD transmit intermodulation – consideration of whether this is an issue that we should seek to raise during a further ETSI review process in the future
  - i) Default WSD sensitivity level used in master WSD coverage area calculation – a value of -114 dBm/100 kHz will be used at the beginning but further consideration will be given to whether a higher level would be more realistic

Ofcom Statement—Further Work Potentially Resulting in Changes

- Identified due to the Pilot and Ofcom's Coexistence testing (text directly from Ofcom Statement)
  - j) Transmissions within PMSE venues – following implementation of venue boundaries, consideration of how to minimise WSD transmission within venues, taking account of the need for slave WSDs to be able to make initial contact with masters
  - k) Determination of generic operational parameters and master-slave association – we plan to review, following the implementation of the approach set out in this Statement, the extent to which master-slave association imposes a constraint on the deployment of WSDs, and if so what changes may be possible and how to address any related risks to PMSE
  - l) Consideration of the ETSI Harmonised Standard – a review of how the current standard could be developed, for example whether new emission classes, or a refinement to the class system for WSDs in relation to their propensity to cause interference to DTT receivers, would be beneficial, so that this can be fed into a future ETSI review process
  - m) Planned consultation on whether to introduce a licensing regime to authorise manually configured devices (i.e. that require the user to determine and specify the device parameters) that will not meet the requirements of the licence exemption

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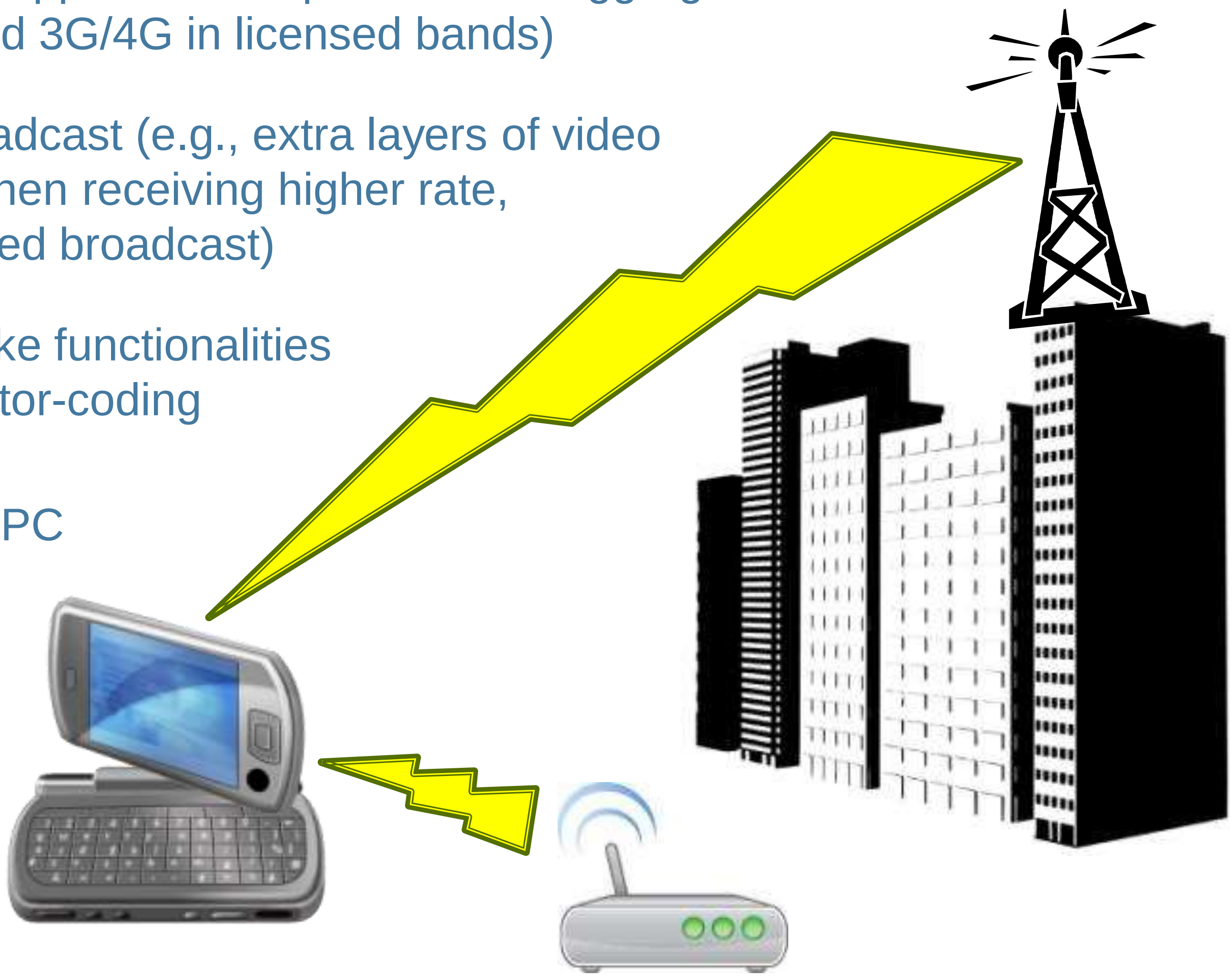
Our Trial

LTE MBMS and Spectrum/Link Aggregation Scenario

- LTE MBMS and opportunistic spectrum/link aggregation with other services (WiFi in ISM, and 3G/4G in licensed bands)
- Augmented broadcast (e.g., extra layers of video subscribed to when receiving higher rate, locally customised broadcast)
- Data carousel-like functionalities achieved by raptor-coding the data set
  - Augmented CPC
  - Software upgrades

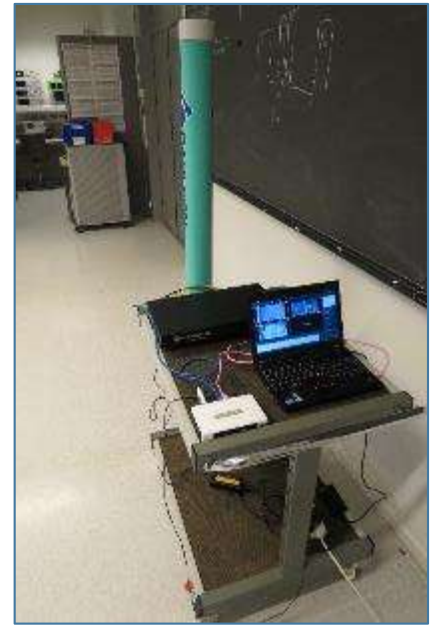


Public Protection and Disaster Relief Scenarios

- Video surveillance system in TV White Space

2 Sony SNC-CH220
+ 1 Carlson Terminal

1 Sony SNC-ER550
+ 1 Carlson Terminal

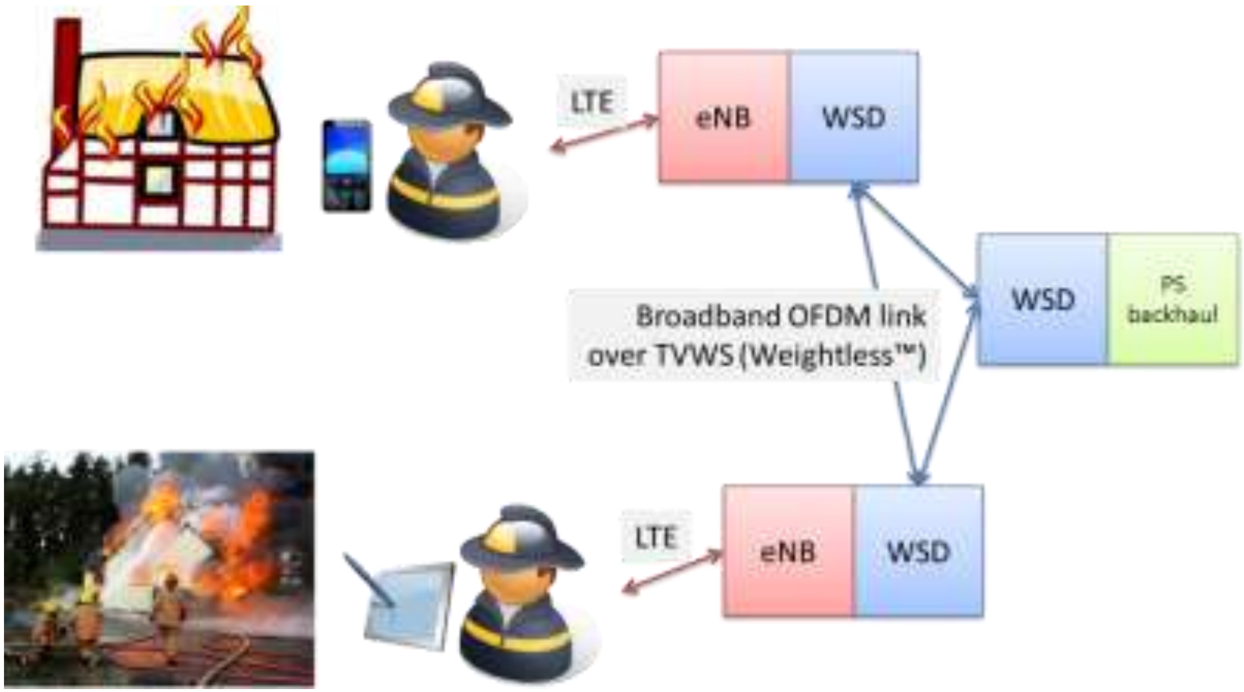


Carlson Basestation

Sony Real Shot manager software

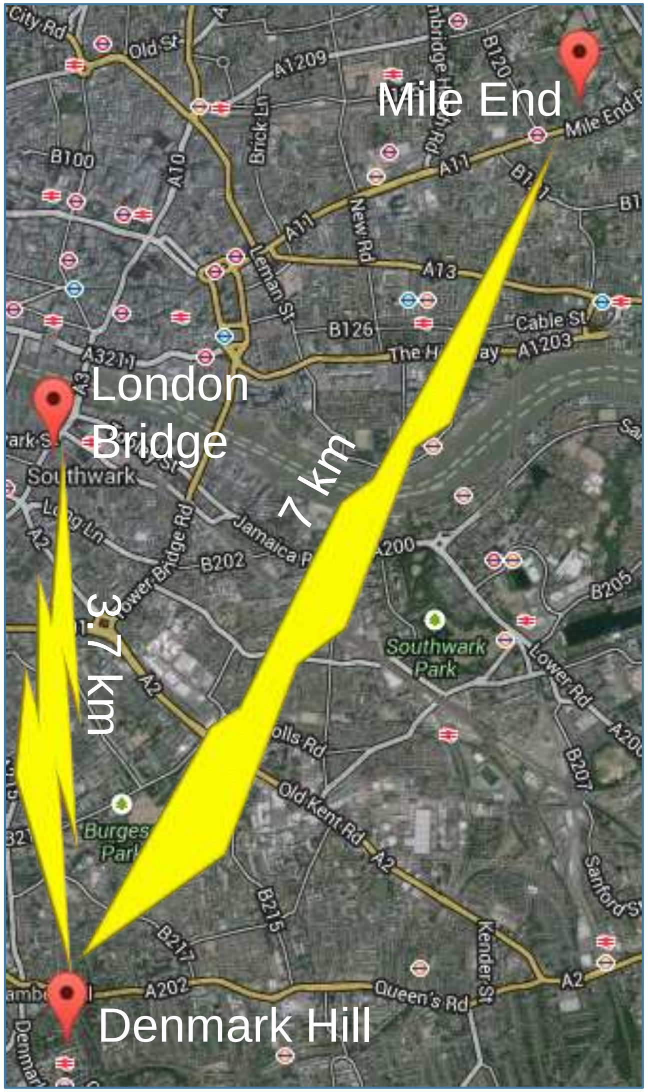
Public Protection and Disaster Relief Scenarios

- LTE femtocells + intercellular links in TV White Space
  - Quickly-deployable field solutions for emergency situations (e.g., enhanced provisioning or coverage extension to emergency workers)
  - Ad-hoc repair of communications links (e.g., backhaul) in disaster scenarios (e.g., earthquakes)



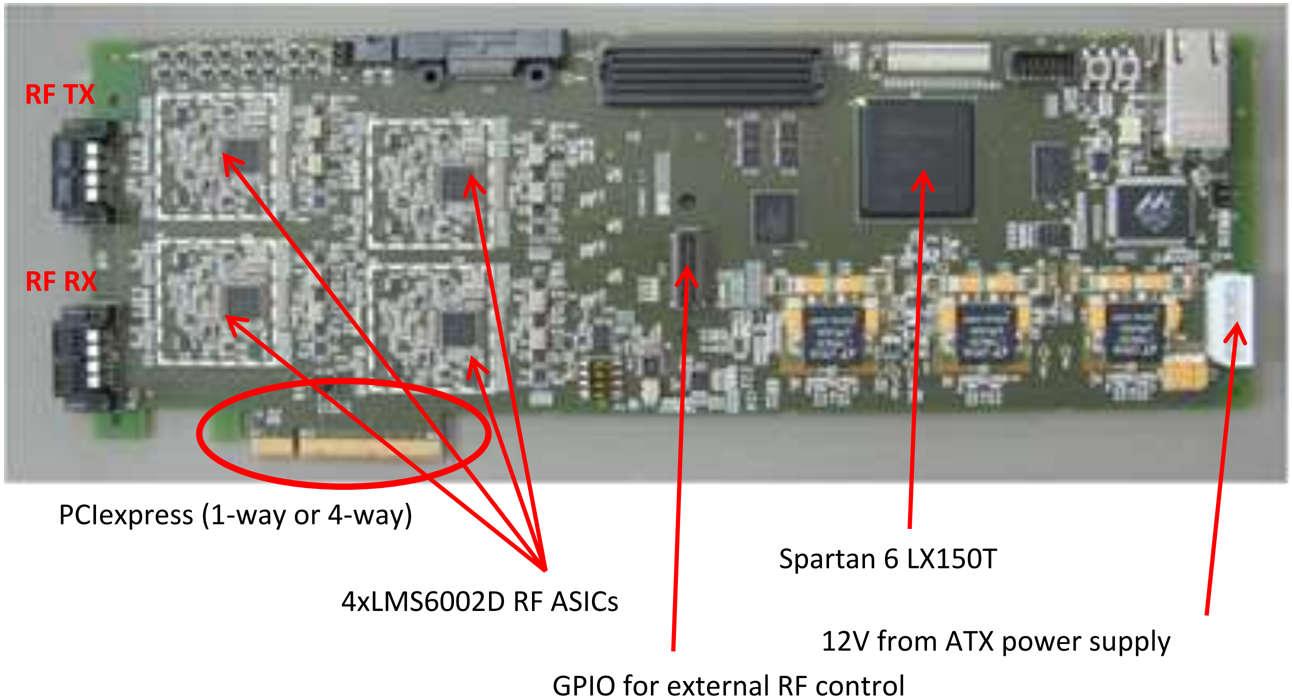
Other Scenarios

- Point-to-point links for backhaul provisioning, between different university campuses of participants in our trials (two challenging examples we will attempt to achieve are to the right)
- General broadband provisioning using a range of devices and systems
- LTE small cell implementations, likely indoor
- Wireless local area networking in TV White Space
- Machine-to-Machine communications in TV White Space (possible at later stage)



White Space Devices: Eurecom ExpressMIMO2

- ExpressMIMO2 is the basis for the LTE MBMS case initially, and likely other LTE cases later—perhaps also 802.11af at a very late stage
- No DSP on board, FPGA primarily used just for routing data; host PC must be powerful and running in a real-time operating system!!! 4 RF chains achievable on the card (all Tx+Rx)
- Have set up 3 devices based on this so far (1 base station and two terminals), each hosted in a PC with (in the case of base station) a separate box handling RF



White Space Devices: Carlson Wireless RuralConnect

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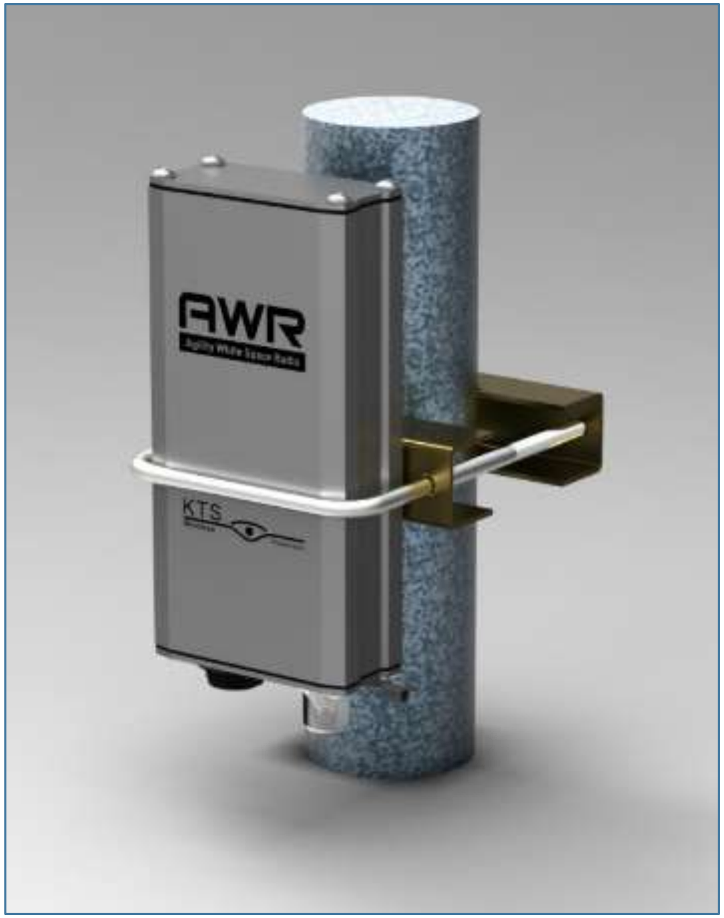
- http://www.carlsonwireless.com/ruralconnect
- Built for US market, but adapted to operate under Ofcom/ETSI rules in terms of database (and database of databases) communication, channelization, etc. Variable powers and (complete) UK frequency range currently not adapted
- Our trial is using at least 2 base stations and 4 terminals (perhaps different sets at different times)
- Deployment scenarios include the public protection and disaster relief cases
- Also broadband provisioning cases, and to test longer-distance point-to-point links

White Space Devices: Sinecom/KTS Agility White Space Radio

- http://sinecom.net/product.html
- There are geolocation database interaction issues being worked through, although it is hoped that they can be solved and the devices used
- In the shorter term, to be used for low-rate broadband provisioning
- In the longer term, likely to also be used for M2M cases
- Likely to be used for the point-to-point long-distance links at a later stage
- Our trials will have at least 6 of these devices



White Space Devices: NICT and Others

- NICT devices deployed for a short duration, in collaboration with NICT
  - TD-LTE in TV White Space
    - Base stations and terminals - 3 of each
    - Used for general testing of LTE scenarios (small/femto cells, and larger cellular provisioning cases)
  - Low-power IEEE 802.11af (WiFi in TV White Space)
    - Wireless local area networking is prime use case
    - 5 of these devices
  - High-power IEEE 802.11af
    - Long-distance backhaul link provisioning
    - 2 of these devices
- Too early to declare the companies involved, but a manufacturer implementing WiFi in TVWS (with channel aggregation), and another implementing WiMAX in TVWS (with channel aggregation), will be joining our Trial in January 2015

NICT Devices (collaboration with NICT—available for short durations)

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- Wireless mesh network deployment example at NICT, Yokosuka, Japan (*very* low Tx power in this case), also with graphical representation of the NICT database implementation

Locations

- London
  - King’s College London Strand
  - King’s College London Waterloo
  - King’s College London Denmark Hill
  - King’s College London Guys (London Bridge)
  - King’s College London St. Thomas’ (opposite Westminster)
  - King’s College London Hampstead
  - Queen Mary University of London
- Outside London
  - University of Surrey (Guildford)
  - University of York
  - Strathclyde University (Glasgow—under discussion)
  - Cambridge University
  - University of Bath
  - Leeds University (back-up)

The Trials Team

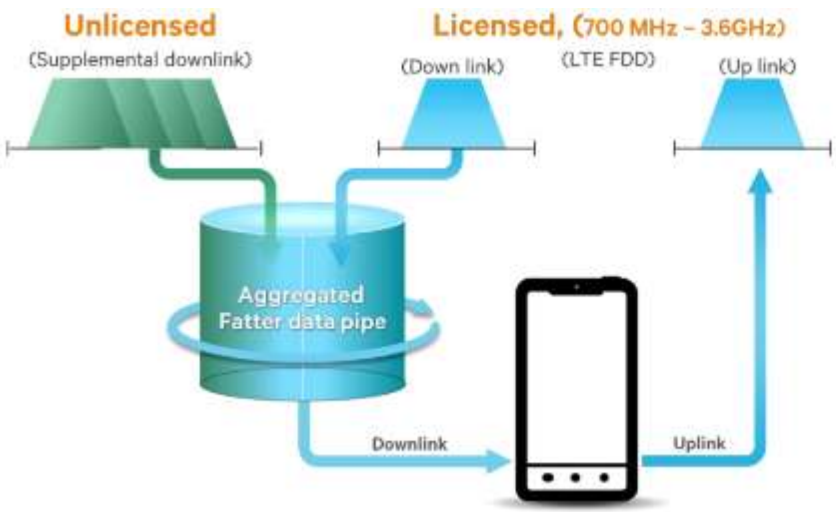
- ACROPOLIS Project
  - Led by
    - King’s College London, UK
    - The Joint Research Centre of the European Commission, EU
    - Eurecom, France
  - Also involving
    - RWTH Aachen University, Germany
    - Saints’ Cyril and Methodius University in Skopje, FYRoM
    - Poznan University of Technology, Poland
    - University of Rome “La Sapienza”, Italy
    - University of Piraeus Research Centre, Greece
    - Institute of Accelerating Systems and Applications, Greece
    - University of Surrey, UK
    - University of Leeds, UK

The Trials Team

- Extensive involvement of other projects, notably ICT-SOLDER (www.ict-solder.eu), ICT-CREW (www.crew-project.eu), Newcom# Network of Excellence (www.newcom-project.eu), ICT-CRS-i (http://www.ict-crsi.eu). Also numerous high-profile individual groups participating
- Following reflects both the above projects participants, and individual groups participating (not exhaustive)
  - Belgium: iMinds, IMEC
  - Finland: Fairspectrum, Turku University of Applied Sciences
  - Germany: Technical University of Dresden
  - Greece: Industrial Sciences Institute
  - Ireland: Trinity College Dublin
  - Italy: CNIT/Politecnic of Torino, Fondazione Ugo Bordoni, Create-Net
  - Japan: NICT, Sony
  - Portugal: IT/University of Aveiro, IT/University of Beira Interior
  - Slovenia: Jozef Stefan Institute
  - UK: Queen Mary University of London, University of York, University of Cambridge, University of Bath, University of Strathclyde/Larkhill, British Telecom, Nominet

Research Examples - Aggregation

- Solutions for Aggregation of resources/links (TVWS resources aggregated with licensed and unlicensed ISM, and channels aggregated in TVWS)
  - As well as assessing performances, to look at technical means of achieving aggregation compatible with ETSI/Ofcom rules (e.g., cross-band scheduling decisions, intelligent database assistance, etc.)
  - LTE in unlicensed spectrum (LTE-U) one among many interesting cases
  - Why not such a LTE-U supplemental downlink in TV White Space license-exempt spectrum opportunities?



Qualcomm White Paper, "Extending LTE Advanced to Unlicensed Spectrum," December 2013

Research Examples – Primary Service Coexistence Assessment

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- Dedicated equipment to look at effect on DTT, e.g., Wavecom devices
  - Signal Power, Modulation Error Rate, SINR, CINR, BER before Viterbi, BER after Viterbi, BER after Reed-Solomon, etc.
- Will devise challenging scenarios to interfere with DTT, within the scope of ETSI/Ofcom rules (e.g., indoor TV antennas in same room as white space device, saturating TV antenna amplifiers, etc.)
- Also plan to test interference with PMSE through our own PMSE equipment, again within Ofcom/ETSI rules. E.g., blind online surveys

Research Examples – Spectrum Monitoring and Statistical Inferences

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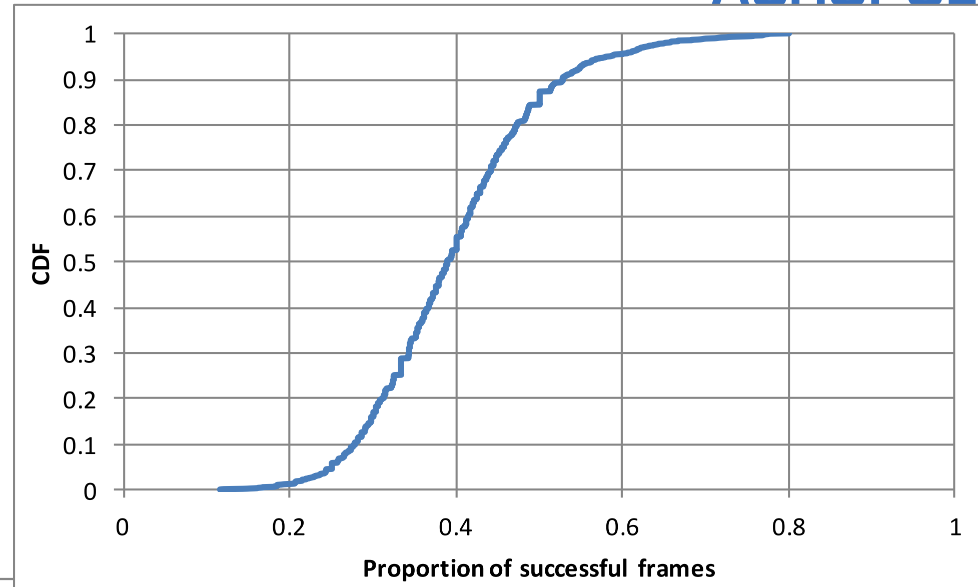
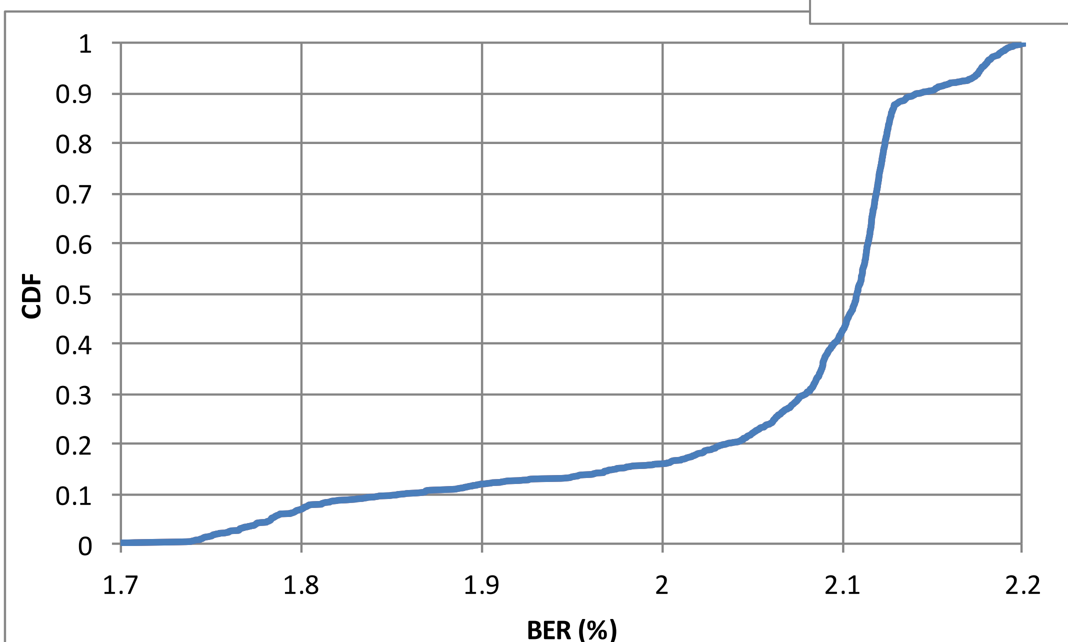
- Long-term fixed measurements or spatially distributed measurements, to assess the effects on the spectrum of TV White Space devices
  - Assessment of correlation aspects of spectrum usage both with and without white space devices present (useful for, e.g., assessing the spatial uncertainty in the effects on the spectrum) that white space devices may have
  - One monitoring location on roof of King's College London Strand Campus

So, What is Achievable in TV White Spaces?: Long-Distance Links

Long-Distance Links

- Denmark Hill to Queen Mary, BPSK ½
- One example





So, What is Achievable in TV White Spaces?: Indoor Strand

Indoor Strand

- Some very early analyses of a vast wealth of statistics! –Far more work to be done in the near future…!
- Link 1 (to Oliver’s Office)
  - 16QAM with no coding - bit error rate typically 10^{-4}
- Rate performance
  - E.g., speedtest, 6.5-8.3Mbps downlink, and 2.6-3.2 Mbps uplink
  - Single 100Mbps file download, 92 seconds → 8.7Mbps average downlink
  - Noted that RuralConnect firmware has been updated and since then we are getting improved downlink of 10-11.5 Mbps; little noticeable improvement on uplink

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So, What is Achievable in TV White Spaces?: NICT Devices

NICT 802.11af (high/low power) and LTE in TVWS

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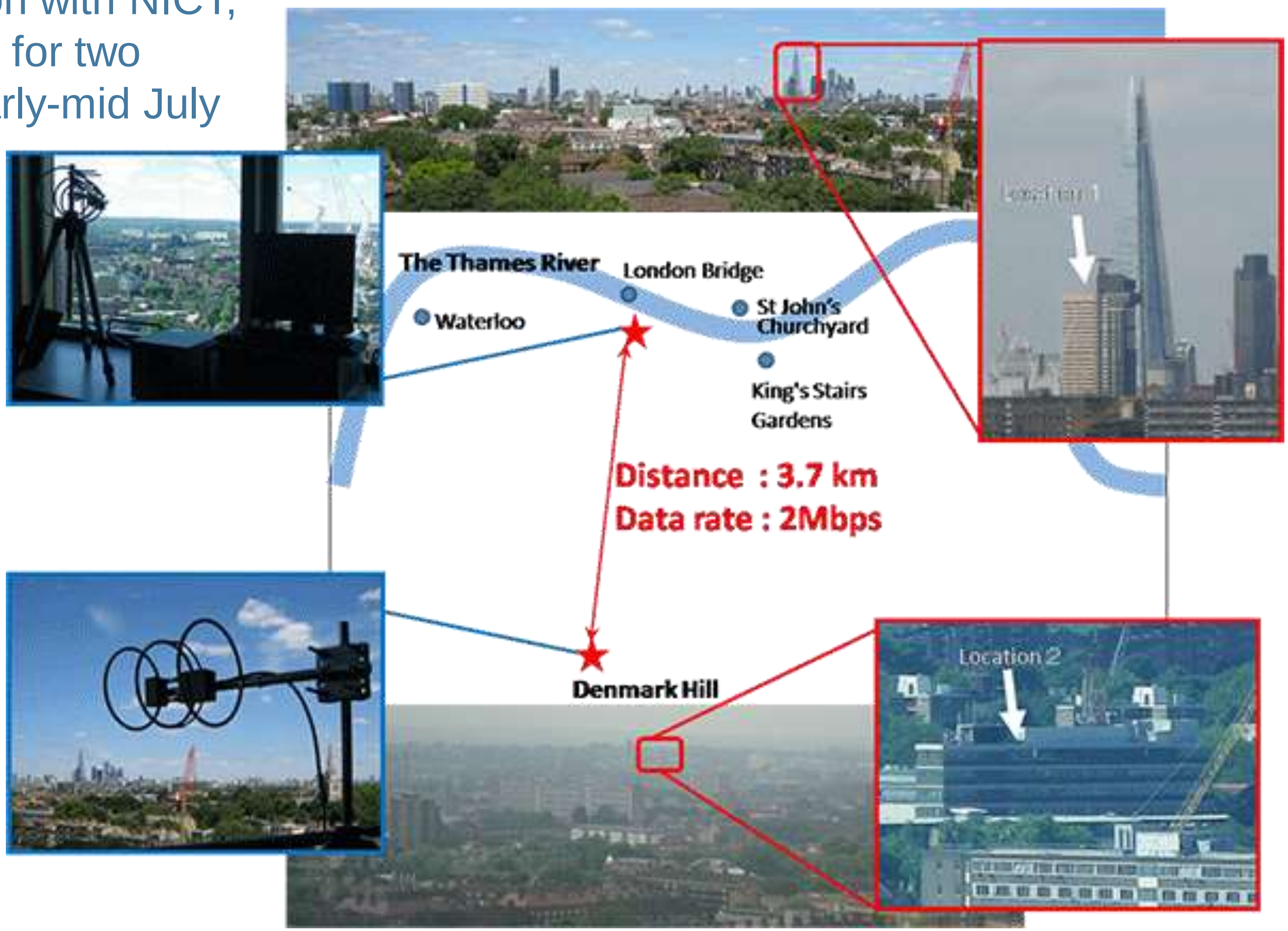
- Collaboration with NICT, visiting KCL for two weeks in early-mid July
- Over 2Mbps achieved across our link from KCL Denmark Hill to KCL Guys (exactly the same scenario as mentioned on previous slides)
  - High-power 802.11af device
- Over 40 Mbps local provisioning using LTE system over three contiguous TV White Space channels in Central London (KCL Guys, London Bridge)

NICT 802.11af (high/low power) and LTE in TVWS

- Collaboration with NICT, visiting KCL for two weeks in early-mid July



So, What is Achievable in TV White Spaces?: PMSE Coexistence

PMSE Coexistence

- Transmitting white space device at maximum allowed power (31 dBm in this case), with PMSE in the main lobe on the adjacent channel at 5m distance from the white space device antenna, PMSE tuned as close as possible to the channel of the white space device on the adjacent channel
- Using analogue FM PMSE, which would be directly (audibly) affected by interference
- PMSE transmitter approximately 6m away from receiver – also tested for highly attenuated / low receive power PMSE scenario (>20dB additional attenuation) by placing PMSE transmitter behind a metal box
- Recorded audio over the PMSE link using audio test files, with and without white space devices transmitting, for blind listening tests
- A video has been made explaining exactly what was done, although not in public domain – please inform if you wish to have access to it