Smart Grid Communications in Rural Areas — Wireless Access via TV White Space Spectrum

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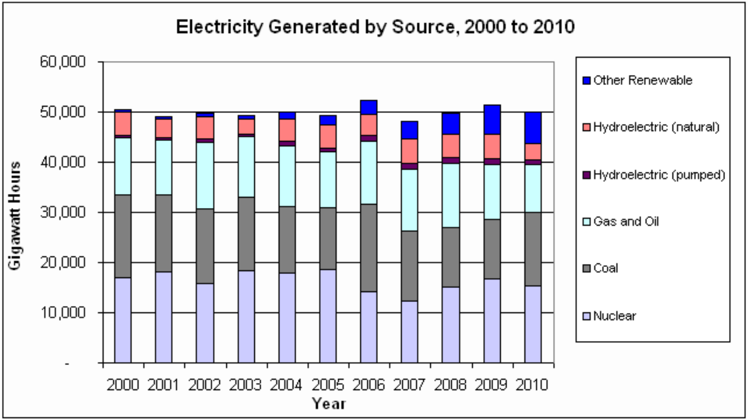
Overview

Part 1: Rural Electricity Grid

Electricity Generation Scotland

- Generation of power in Scotland from 2000–2010 by source



[Source — "Electricity Generation", Scottish Government, December 2011.]

- increased downtime on nuclear reactors in 2008 & 2009
- low rainfall in 2010 $\longrightarrow$ reduction in hydro

Current and Future Energy Supply

- European energy policy extracts:
  - sustainability (20:20:20 targets): 20% reduction in greenhouse gases, 20% increase in energy efficiency, 20% from renewable energy sources by 2020
  - security of supply: [...] improve security of energy generation
- Scottish government targets:
  - Scottish Government's Climate Change Act "sets a target of reducing emissions by 80 per cent by 2050, including emissions from international aviation and shipping. It also sets a world-leading interim target for a 42 per cent cut in emissions by 2020."
  - Renewables Policy "[...] renewable sources to generate the equivalent of 100 per cent of Scotland's gross annual electricity consumption by 2020. Similarly, a target has been set for renewables sources to provide the equivalent of 11 per cent of Scotland's heat demand by 2020."
    [Source: "The Routemap for Renewable Energy in Scotland", Scottish Government, June 2011.]

Renewable Energies in Scotland

1. Latitude and weather mostly exclude solar and photovoltaics
2. Rough weather and costal location offer advantages
   2.1 on- and off-shore wind power
   2.2 hydroelectric power
   2.3 tidal power
   2.4 wave power

Hydro-electric Power

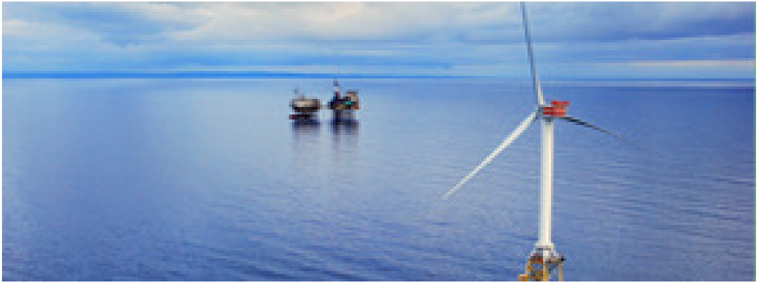
- Dams and reservoirs for hydro-elecric power (mostly for aluminium smelting) since 1950s.

Small Hydro-Electric Schemes

- Powers small communities — a fairly recent development.

Onshore Wind Power

Offshore Wind Power



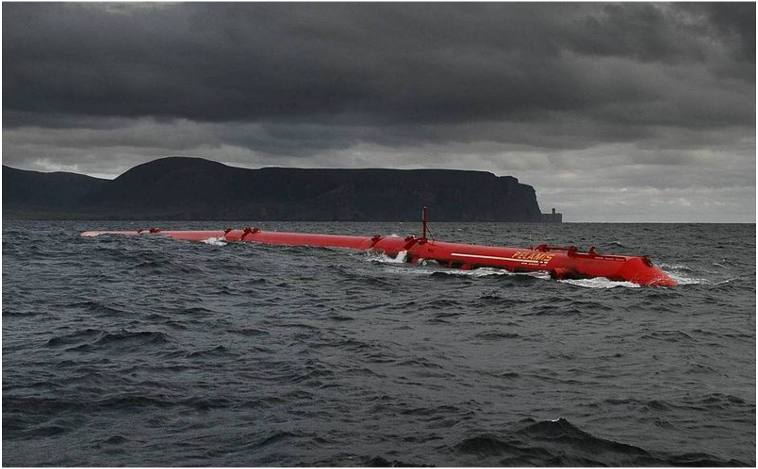
Tidal Power

- Deployment — 10 in Islay Sound, 100 in Pentland Firth by 2013 [BBC, May 17,.2012]

Tidal Energy

- 30m tall, 1MW

Wave Power



- Pelamis (Edinburgh designed and made) consist of 5 articulated segments, articulating joints creates hydraulic pressure and is converted into electrical energy

Wave Power II

- current design is 180m long, 4m diameter, yielding 750kW output
- cable connection to land base

Current Use and Potential of Renewables

- overview over current and potential power from renewables (based on prospective sites)

technology	current power	potential power
onshore wind	2.7GW	11.5GW
offshore wind	0.2GW	25.0GW
tidal	1MW	7.5GW
wave	1MW	14.0GW
hydro	1.4GW	1.6GW

- current power makes up the $\approx 20\%$ share in generated electricity
- target therefore seems realistic but requires delivery and control of generated power.

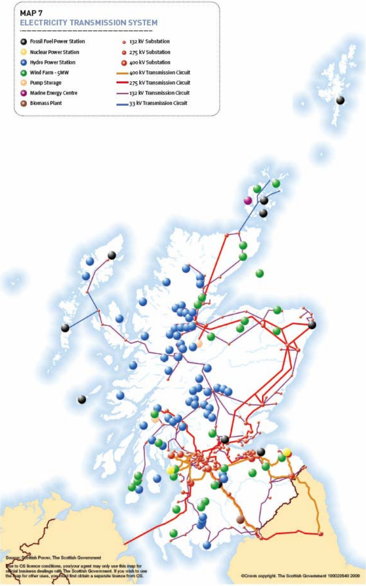
Deployment Locations

- map indicating current and prospected locations for renewable power generation
- site are in their majority at the periphery

Transmission and Distribution Network (Scottish Power Energy Network, Central Scotland)

- Transmission network (440kV, 275kV, 132kV)
  - 3,900km overhead lines
  - 247km underground cable
  - 19 substations
- distribution network (33kV, 11kV, 400/230V)
  - 24,500km overhead cable
  - 40,900km underground cable
  - 41,350 substations

Transmission and Distribution Network II



- Hydro-electric
- Wind farm (¿5MW)
- fossil fuel
- nuclear
- (substations)

Smart Grid Aspects and Definition

- What motivates and encompasses the Smart Grid?
  - Distributed generation
  - Peak power constraints
- etc.

Smart Grid in Rural Area

- Rural areas often peripheral, traditionally centralistic hierarchy means weak / poor infrastructure
- Distributed generation particularly in rural areas (tidal, wind, hydro, etc)
- Island modes — even in self-sustaining communities, during link failure power generation is shut down to avoid asynchronous operation

Part 2: Smart Grid Functions Requiring Communications

- Automatic meter reading
- demand side control for peak power reduction
- phase / load balancing
- re-synchronisation after faults, re-connection of islands

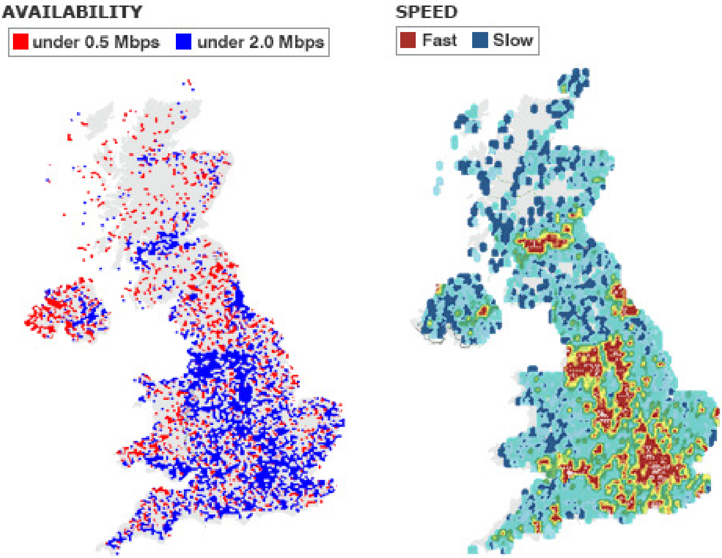
Infrastructure Problems

- Electricity grid in Scotland is dated and fragile
- hierarchical grid organisation does not support renewable energy generation at the periphery
- a communications infrastructure is required to measure, regulate, and control various aspects of the electricity grid, ranging from remote meter reading to demand side control, load shedding, or phase balancing
- various communications options have been pursued for smart grid applications
  - power line communications
  - wireless — WLAN/WiMAX, WiFi, Bluetooth, ZigBee, satellite, etc.
  - wireline — DSL, powerline
  - optical links
- not all of these options fit a rural/remote setting

Communications Infrastructure in Remote Locations

- Optical — expensive if laid over long distances and in rocky ground
- the Scottish Highlands and Islands have no or only very poor 3G coverage
  $\longrightarrow$ some wireless solutions unsuitable
- satellite communication is very costly
- many premises are located more than 3.5 km from telephone exchanges
  $\longrightarrow$ DSL poor
- few subscribers and long distances generally means poor return on investment for most communications techniques
  $\longrightarrow$ operators will not provide infrastructure unless heavily subsidised.

DSL Quality in the UK

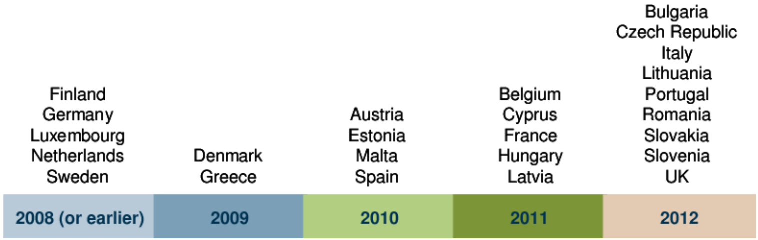


[Source — DC-KTN report "Achieving Rural Broadband through Wireless Solutions", 2010]

Part 3: TV White Space Communications

Switch-Over to Digital Broadcasting

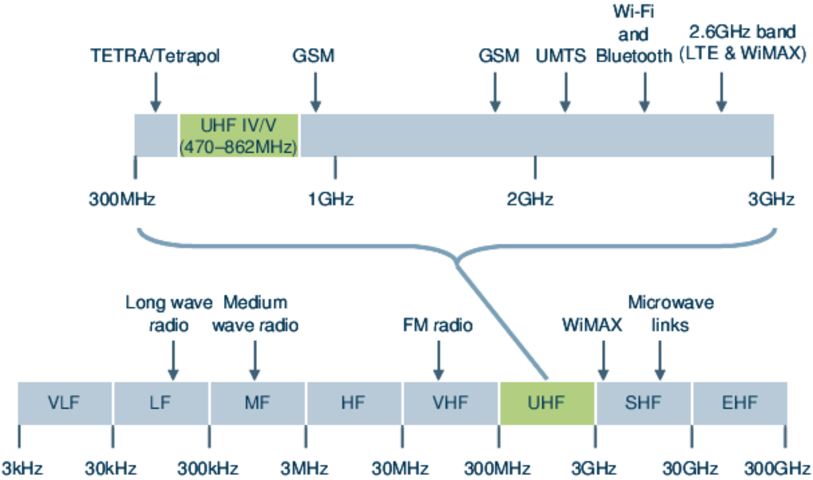
- Most European countries have been completing the switch-over from analogue to digital broadcasting of television content



- using the digital video broadcasting — terrestrial (DVB-T) standard, the spectrum efficiency is enhanced compared to analogues transmission
- the total TV offering is compressed into 6 bands (or "multiplexes"), of which three cover the free public services
- the potential economic exploitation of the freed bandwidth is referred as the "digital dividend".

TV White Space Communications

- TV broadcasting is located in the UHV band



- we will later see that this spectrum offers better propagation characteristics than e.g. WiMAX bands at 2 and 5GHz

UHF Channel Structure

- analogue broadcasting resided in the UHF spectrum

- a number of bands have been freed
- the upper range are in the process of being actioned off for mobile services providers
- concerning the remaining channels, availability is dependent on geography
- radio microphones as legacy users have priority

TVWS Interest

- The upper part of the UHF spectrum is likely to be licensed to mobile services providers
- the benign characteristics make UHF channels “beach-front” spectrum
- the likes of Google and Microsoft are pushing for license-free access to other parts in order to offer services for i-phone, skype etc.
- Microsoft refer to TVWS as “Super-WiFi”
- Broadcasters are sceptical and very conservative!

Geographical TVWS Availability

- e.g. London with its many theatres has a large spectrum occupation by radio microphones
- availability of TVWS spectrum appears inversely proportional to the population density

TVWS Trials

- A number of trials for TVWS have been under way, mostly in the area of broadband access
- Rice Networks group uses both WiFi and UHF to deliver broadband to underpriviledged and underserved communities, plus additional trials starting
- Cambridge White Spaces trial — mostly a forum of interested industrial parties, who have demonstrated a point-to-point link
- Bute trial — supported by the Technology Strategy Board, this trial has been running since April 2011, with 10 customer premises connected, using both UHF and WiFi
- a number of WiFi-based projects have been running in Scotland to address the lack of rural communications infrastructure, including a project by the University of Edinburgh and community-owned and -operated networks such as Tiree.

Cambridge Trial

- Cambridge Wireless is an industry forum based on Cambridge UK
- one set of its activities is the Cambridge White Spaces Trial
- some limited point-to-point demonstrations of TVWS technology have been performed earlier this year, based on a test license for TVWS channels by OFCOM.

Bute and Tiree Trials

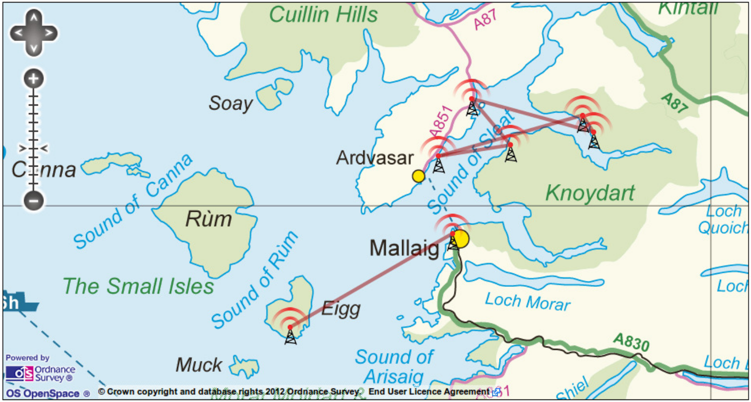
- Technology Strategy Board project on "Extending Broadband Reach" with partners
  - Steepest Ascent Ltd
  - University of Strathclyde
  - British Telecom (including both BT Research and BT Openreach)
  - BBC
  - Berg Design
  - NetPropagate
- trials on channel 57 on the Isle of Bute, with a 19GHz microwave backhaul to the mainland and 10 customer premises connected on the island
- trial operational since mid-2011
- replacement of a 5.2GHz WiFi-based community-owned network on Tiree.

Rice Networks Group

- Rice University is running a community project using TVWS and WiFi to deliver broadband access to under-priviledged and under-served areas in Houston
- project in Argentina on regional infrastructure
  - rolling landscape
  - foilage from vegetation
  - to serve approx. 800k people, with a mix of urban and rural
- currently uses off-the-shelf products with modification similar to what is demonstrated in the Bute trials.

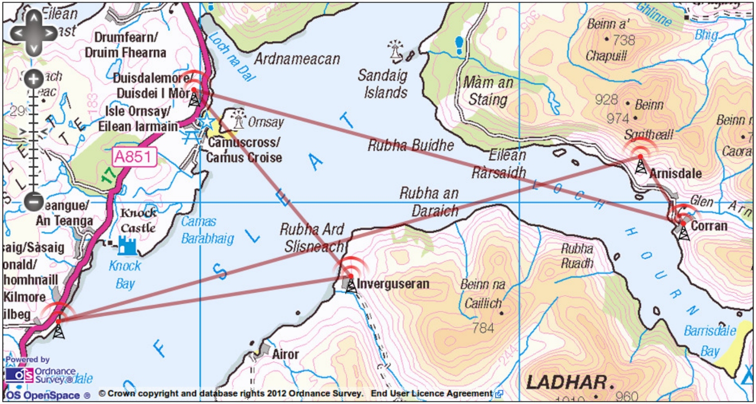
Tegola Project

- similar to the Tiree community network, this uses 5.2GHz WiFi on the North-West coast of Scotland to connect a number of communities



Tegola Project II

- run by Informatics Forum, University of Edinburgh, the focus of this project is on networking issues



- ring structure for security in case of a node failure

Tegola Project III

- the nodes are autonomous, with batteries charged by both PV cells and a wind turbine

Tegola Project IV

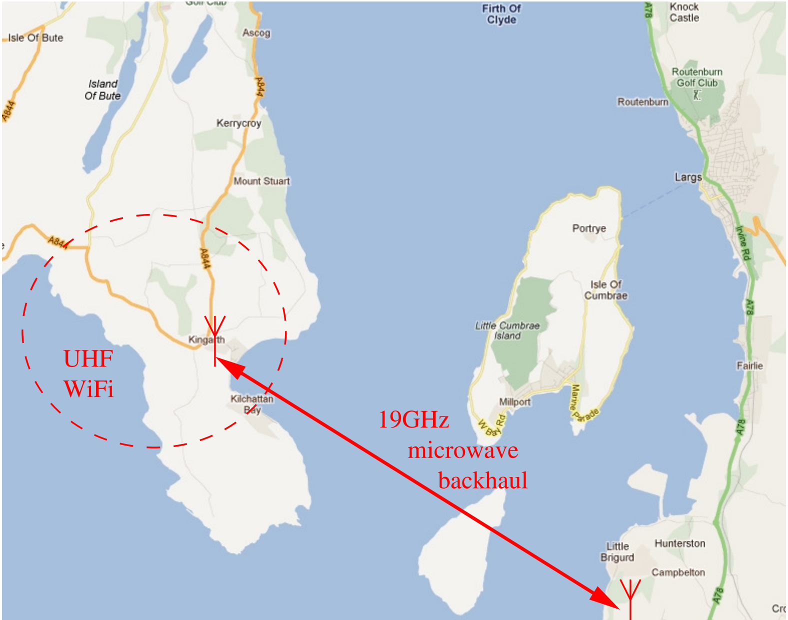
- Operating at 5.2GHz, the system must rely on LOS transmission

HopScotch —
Rural Broadband Access Trials in Scotland

- "White space" communications has been suggested previously as a suitable means for rural broadband access [e.g. Ghassemi et al., 2010 and Reed et al. , 2010]
- HopScotch is based on low-power renewable "WindFi" basestations
- radios operate in 5GHz band (20MHz bandwidth) for line of sight connections
- additional white space overlay network using an 8MHz TV white space channel — WiFi MAC layer with clock division by 4 giving a 5MHz bandwidth
- trial location
  - Isle of Bute — UK Technology Strategy Board project (Strathclyde, Steepest Ascent, BT, BBC, Berg Design, and Netpropagate)
  - Tiree — replacing an earlier community-owned system.

HopScotch Network — Bute

- bla



Isle of Bute — Coverage Area

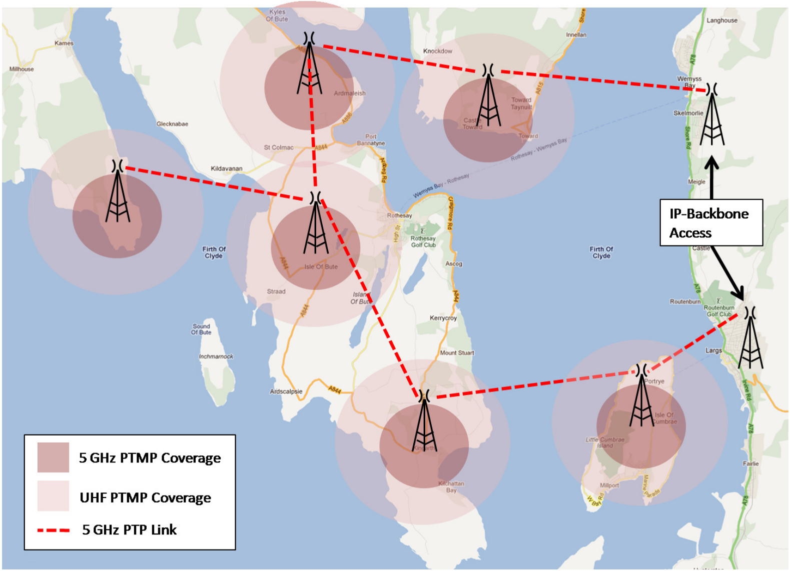
- bla

Isle of Bute — Equipment

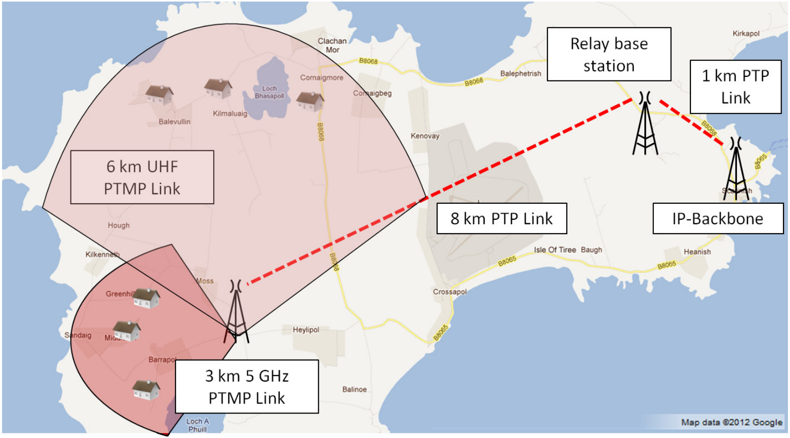
- telephone exchange

- 10 customer premises

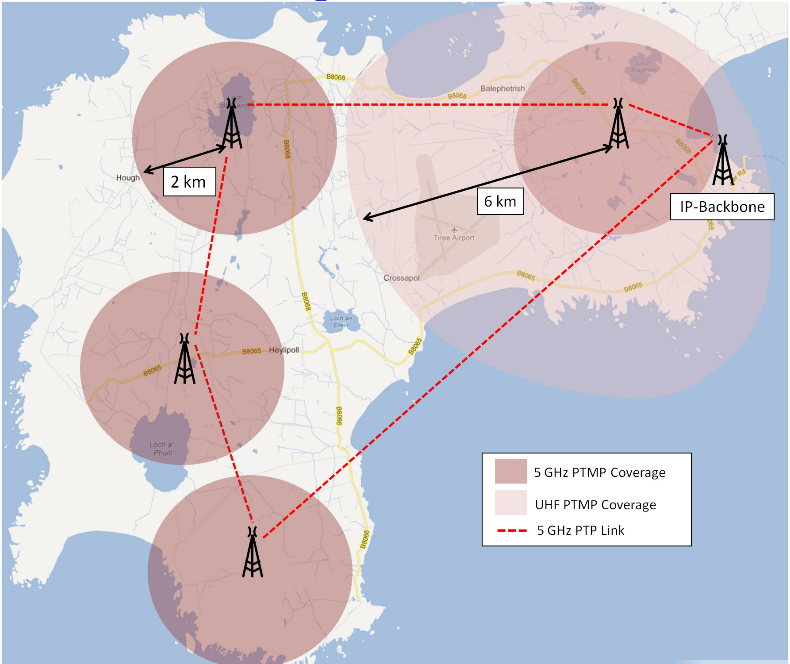
Isle of Bute next step . . .



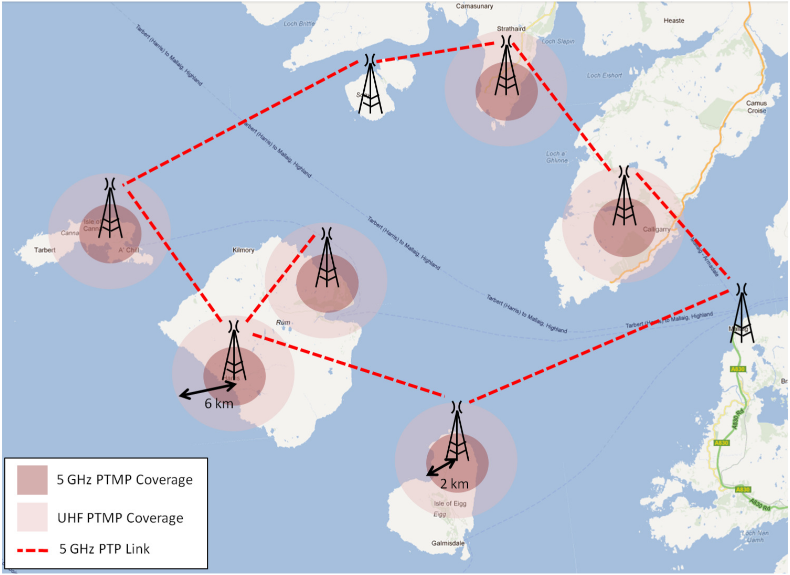
HopScotch — Tiree



Tiree — Potential Ring Network



Mallaig — Potential Ring Network



“WindFi” Base Station

“WindFi” Base Station

- Six radios for sectorised point-to-multipoint (PTMP) and point-to-point (PTP) transmissions, with maximum power 30W
- powered by four 80W solar panels and a 200W wind turbine, a battery bank of 600Ah in the foot of the mast can run the system for 3 days without charge
- no requirement for a fundation and grid access means no planning permission is required in the UK
- 802.11n offering multiplexing, channel bonding, and frame aggregation to maximise throughput
- PTP — 5GHz band C (lightly licensed), 2x2 MIMO with vertical and horizontal polarisations, EIRP 4W, achieves a maxmimum of 300Mbps
- PTMP
  - 5GH band B (unlicensed), EIRP 1W, achieves 3km LOS transmission with a maximum of 65Mbps
  - TV white space (channel 57), 5MHz bandwidth, 6km NLOS transmission

WiFi Wireless LAN Spectrum

- 5 GHz and 2.4 GHz spectrum and equivalent isotropically radiated power (EIRP) limitations in the UK for outdoor use [source: OFCOM].

Band	5 GHz Band B	5 GHz Band C	2.4 GHz
Frequency Range	5470-5725 MHz	5725-5850 MHz	2400-2483.5 MHz
Bandwidth	255 MHz	125 MHz	83.5 MHz
20 MHz Channels	11	5	4
40 MHz Channels	6	2	2
License	License exempt	Lightly licensed	License exempt
Maximum EIRP	1 W	4 W	100 mW

WindFi — Antennas

- Two single board computers can hold three radios (2x PTMP and 1xPTP) each

Optimum Spectrum Use

- Comparing between UHF and WiFi (5.6GHz)
- utilising both bands permits a selection
- consider the following scenarios
  - free space path loss
  - terrain effects and diffraction loss
  - influence of foilage

Free Space Path Loss

- Given two frequencies f_1 and f_2, the distances $r_{(f_i)}$ of equivalent pathloss related by Frii's transmission equation

$$r_{(f_1)} = \frac{f_2}{f_1} r_{(f_2)}$$

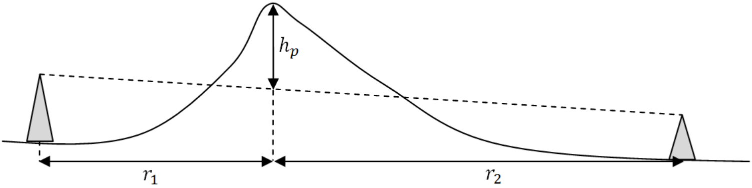
- at 630MHz (mid-UHF band), range is 9 times greater than at 5.6GHz
- transmit powers to achieve the same receive powers at the same distance

$$P_{(f_1)} = \left(\frac{f_2}{f_1}\right)^2 P_{(f_1)}$$

- in the 5.6GHz band, the transmitter must affort a 19.1dB higher transmit power to achieve same distance and receive power.

Terrain Effect and Diffraction Loss

- Propagation loss under non-LOS conditions
- knife edge diffraction can be assumed if obstruction is large compared to the wavelength



- approximation by Fresnel diffraction parameter

$$\nu \approx -h_p \sqrt{\frac{2(r_1 + r_2)}{\lambda r_1 r_2}}$$

- higher diffraction loss at higher frequencies — 5km link, h_p=30m obstruction 900m from TX leads to a 9.4dB drop for 5.6GHz compared to UHF.

Foilage

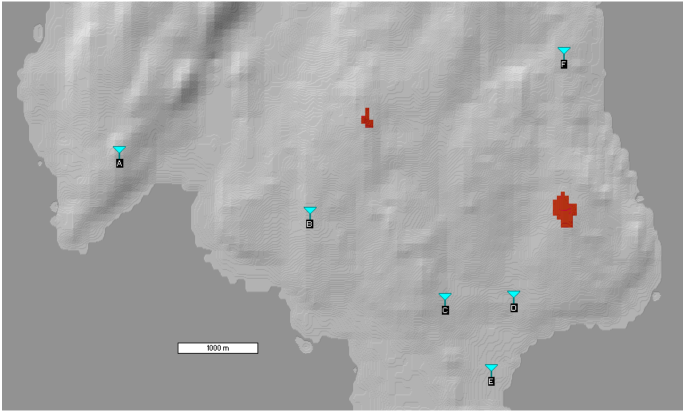
- Clutter such as vegetation and foilage affects propagation
- attenuation is dependent on both frequency and polarisation
- large vertical components in vegetation lead to a stronger attenuation of vertical compared to horizontal polarisation
- propagation loss due to Weissberger's model for f (in GHz) and d (in m)

$$L = \begin{cases} 0.45 f^{0.284} d & \text{for} \quad 0 < d < 14 \\ 1.33 f^{0.284} d^{0.588} & \text{for} \quad 14 < d < 400 \end{cases}$$

- at a foilage depth of 10m, a 5.6GHz waveform is attenuated by 7.4dB, while at UHF this is only 4dB.

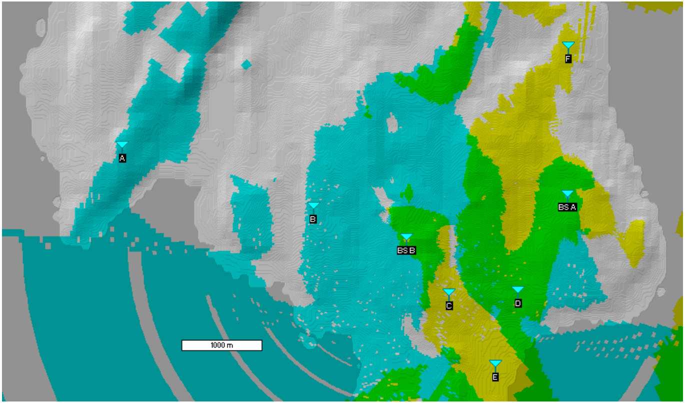
Network Design Considerations — UHF

- Comparing optimum base station placement using he Radio Mobile planning tool for UHF and 5.6GHz WiFi
- example community with 10m base station location shaded in red



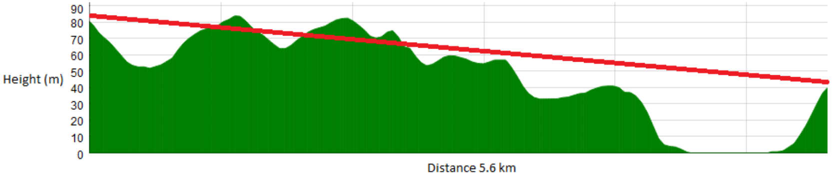
Network Design Considerations — 5.6GHz

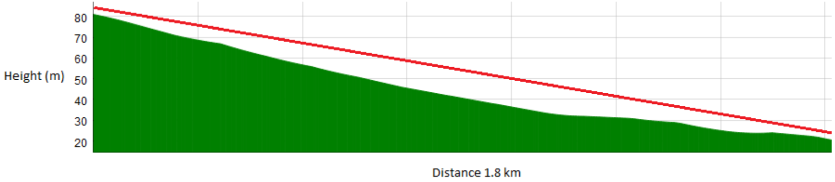
- at 5.6GHz, no one single base station can cover all users
- two base stations, BSA (blue) and BSB (yellow) can provide coverage, with the overlap shown in green



Link Comparions

- Consider links with two different terrain profiles (BSA and users A and D)





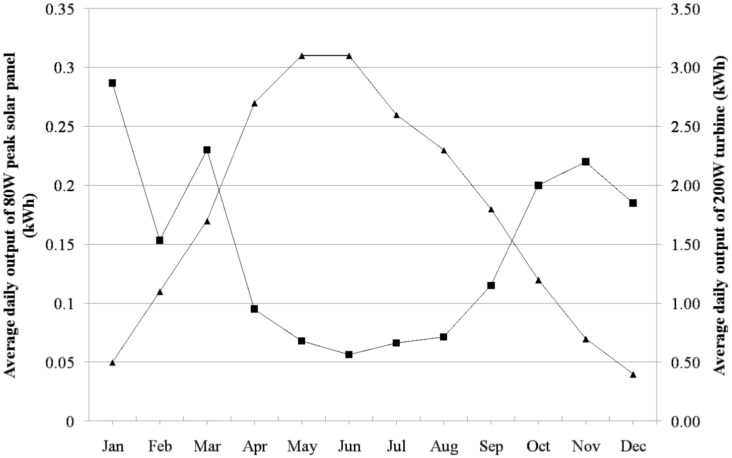
Link Comparions II

- Losses and TX/RX power levels

Node	A @ 630 MHz	A @ 5660 MHz	D @ 630 MHz	D @ 5660 MH
Distance	5.60 km	5.60 km	1.35 km	1.35 km
Path Loss	117.8 dB	144.6 dB	97.2 dB	114.6 dB
Rx Level @ 1 W EIRP	-74.3 dBm	-101.1 dBm	-53.7 dBm	-71.1 dBm
Tx power @ -85.0 dBm	5.8 dBm	32.6 dBm	-14.8 dBm	2.6 dBm

Renewables Aspect

- Similar to Tegola, a mix of wind and solar power is utilised, motivated by the weather (measurements from Isle of Tiree)

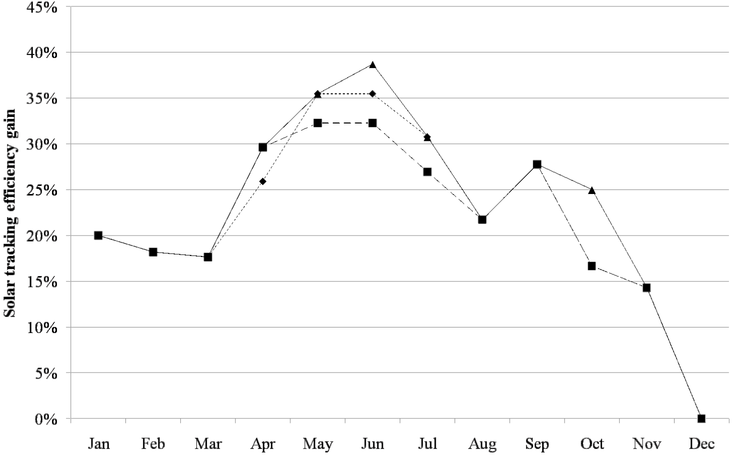


Battery Charge

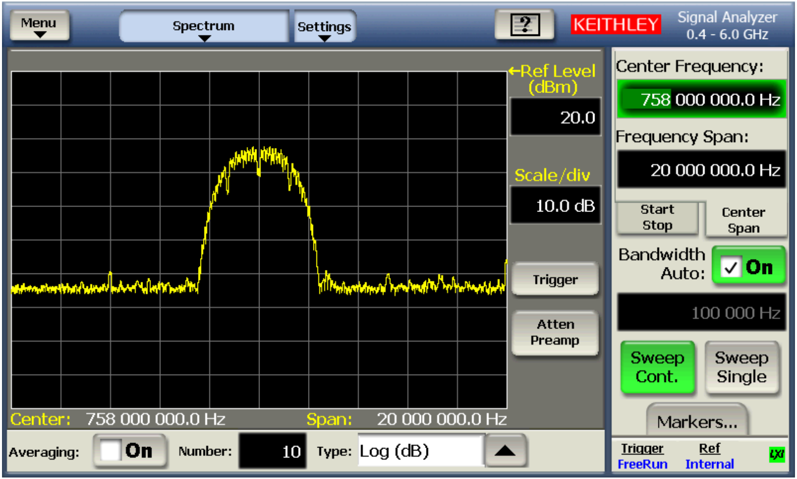
- Power consumption-
  - two single board computers totalling 10W
  - six radios each 5W
  - control aspects, rotating panels etc. $<$5W
- battery considerations-
  - charge depth
  - recharging period
- assuming a 50W base load, 80W PV and 200W wind, a 600Ah battery bank can operate without charge for 3 days and recharge from a maximum charge depth over 5 days.

Solar Tracking

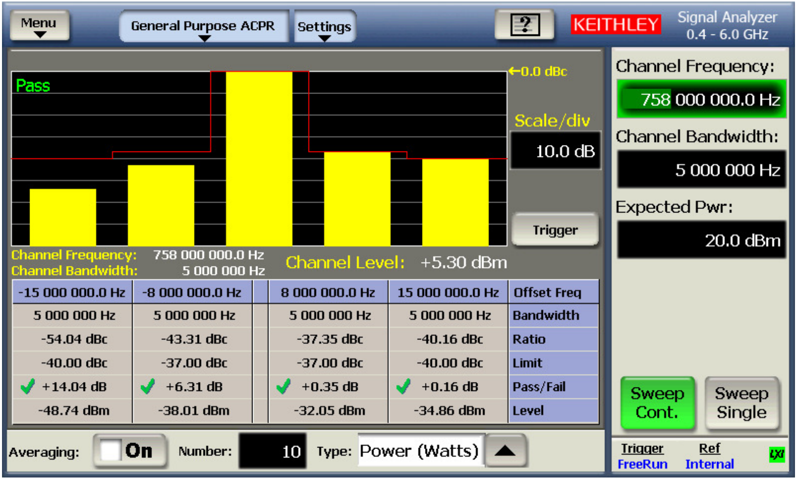
- Options are to rotate PV panels around a vertical or horizontal line, or both



UHF Signal Transmission — Lab



UHF Signal Transmission — Lab II



Throughput Measurement

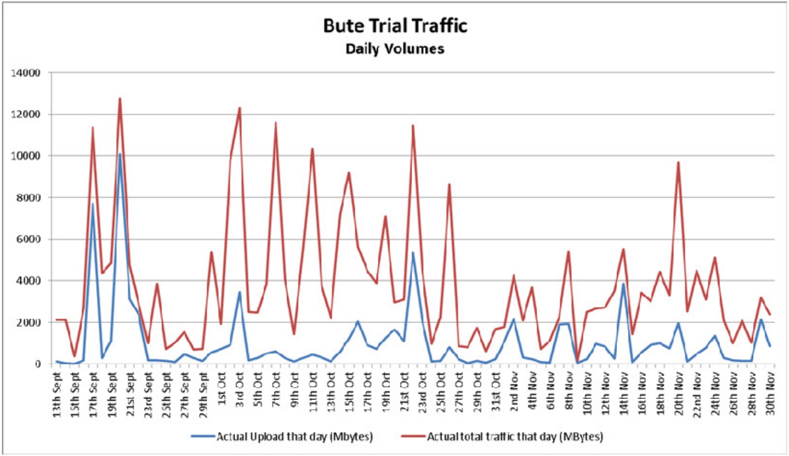
- TCP throughput measurement have been performed
- Isle of Bute — 3Mbps over 5MHz channel on a 4.8km non-LOS link at 2W EIRP
- in excess of 10Mbps on a 2km LOS link
- Tiree — 80Mbps over 9km 5GHz band C PTP link
- 20Mbps over a 3km 5GHz band B PTMP link

System Performance and Trial Outcomes

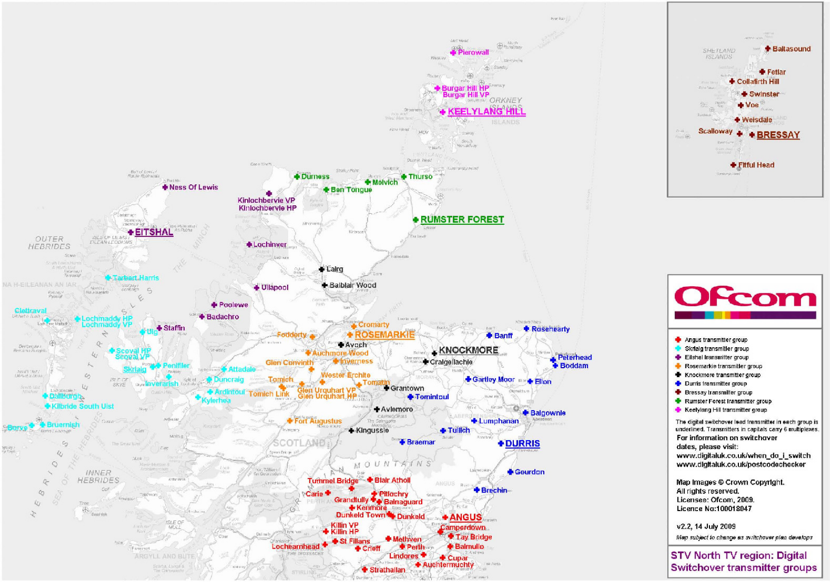
- Base station with white space overlay can achieve an area of coverage that is significantly larger than in the 5GHz region, and not dependent on LOS conditions
- this permits either lower density of base stations, or lower transmit power
- TSB project trial is providing a number of users with high data rate broadband access on Bute (8Mbps at the Brew residence)
- the access is sufficient to run teleconferencing and video streaming (BBC iPlayer) applications
- on Tiree, 28 households are currently connected
- the HopScotch network enables relatively inexpensive wireless rural broadband access.

Usage Statistics

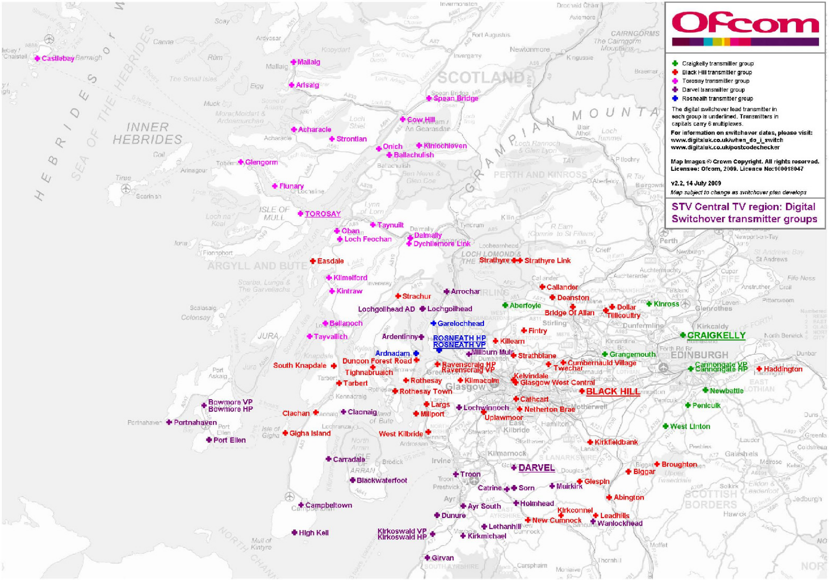
- Traffic volume measured on the Isle of Bute over a period of 2.5 months



TVWS Problems



TVWS Problems II



TVWS Problems III

- TV broadcast patchwork very complicated, danger of adjacent of co-channel use even if not expected

PA20 9NR		
West Kilbride	90-97	41,44,47
Black Hill	62-75	40,43,46
Darvel	79-93	22,23,25,26,29,29

PA20 9LX		
South Knapdale	50	53,57,60
Rothesay	45-57	22,25,28
Girvan	37-74	50,55,59

PA20 0JD		
Rothesay Town	100	50,55,59
Rothesay	100	22,25,28
Rosneath	60	53,54,57,58,60,61

PA20 9PA		
Rothesay	99	22,25,28
Rothesay Town	55-65	50,55,59

- strict adherence to spectral masks required.

Signal Strength and Interference Measurements

Trial Outcomes

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Relevance to Smart Grid Communications

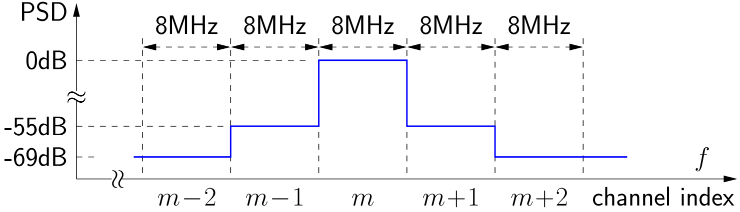
- The focus of our current projects are the provision of rural broadband access
- HopScotch can enable in-home smart grid systems that would otherwise be connected via DSL
- smart grid devices might be wirelessly connected within a PTMP sector
- current schemes use TDMA or CSMA in connection with OFDM — for low data rate applications, the current protocol needs to be amended and could e.g. utilise filter-bank based transceivers
- future schemes would feature cognitive radio characteristics, with an adaptive channel allocation that is driven by GPS and geographical data bases
- in the meanwhile, e.g. Tiree produces more energy from wind than it consumes, and smart grid schemes with associated infrastructure requirements are needed.

TVWS MAC/PHY Layer Standards and Developments

- Existing standards — WiMAX (802.16), LTE (3GPP), WiFi (802.11)
- evolution of TVWS standards — ECMA 392, IEEE 802.22, IEEE802.11af
- evolution of standards targetting coexistence and dynamic spectrum access — IEEE 802.19.1 (coexistence), P1900.4a (dynamic spectrum access), ETSI RC RRS (reconfig. radio systems)

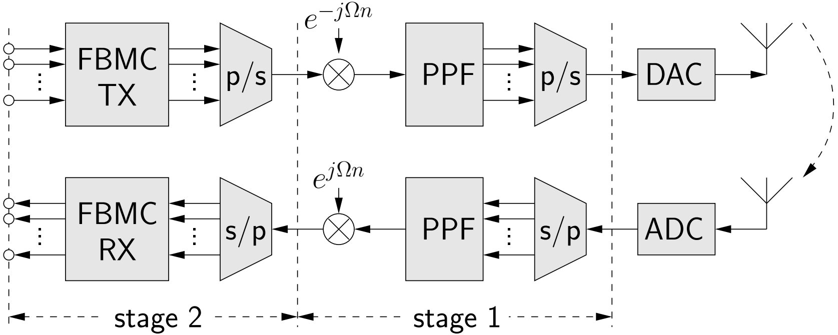
TVWS Transceiver Project

- The trials have shown that stringent satisfaction of spectral masks is required
- Spectral mask defining PSD levels in adjacent $(m \pm 1)$ and next-adjacent $(m \pm 2)$ 8MHz TVWS channels [FCC, Schellhammer 2009]



TVWS Transceiver — Proposed System

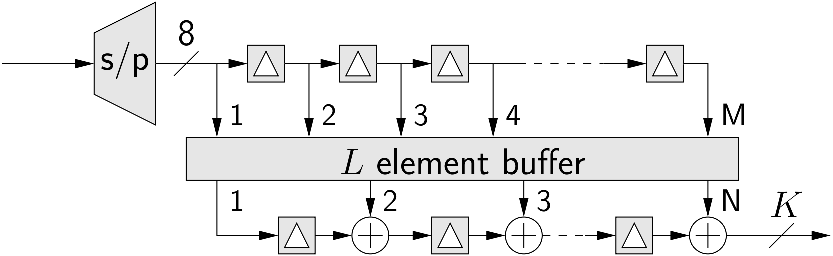
- Sampling at RF with f_s =2.688Gsps
- up/down-conversion in two stages, with the problem of interfacing an FPGA to the RF interface



- flexible up-/down-conversion ...

TVWS Transceiver — RF Interface

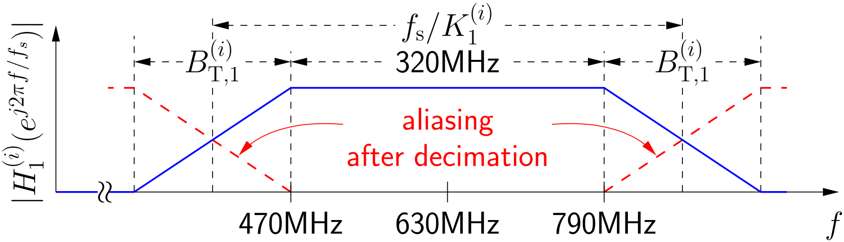
- FPGAs capable of inputs ≈ 600Msps maximum
- therefore, a hardware multiplexer / demultiplexer can be used to create a number of parallel data streams



- the flow graph shows the multiplexer (TX), with an analogous demultiplexer to be utilised in the RX.

TVWS Transceiver — Stage 1 Characteristic

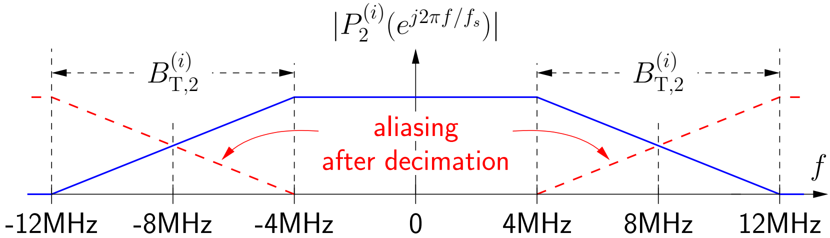
- Stage one in the Rx extracts the 320MHz UHF band



- recall that decimation of a complex value signal only needs to take into account the signal bandwidth, not its band position
- "demodulation by undersampling" ...

TVWS Transceiver — Stage 2 Characteristic

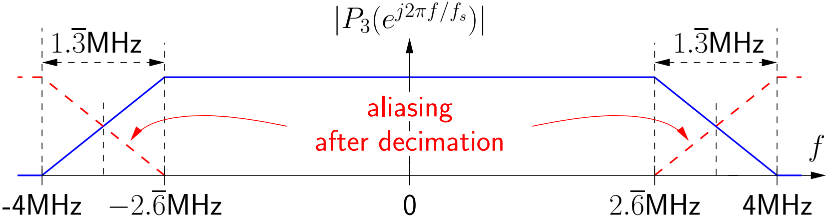
- Stage two extracts the 40 TVWS channels



- it is assumed that each 8MHz TVWS channel is oversampled by a factor to 2
- this enables e.g. fractionally spaced equalisation for synchronisation and equalisation.

TVWS Transceiver — Stage 3 Characteristic

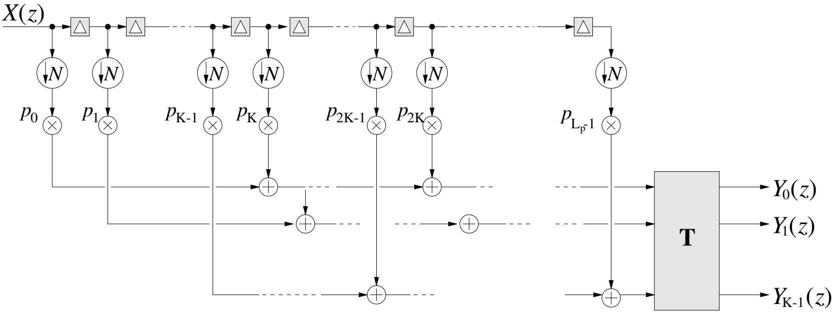
- This stage is for test purposes only to enable an example transmission within the 2-times oversampled TVWS channels



- like stages one and two, a root-Nyquist characteristic is sought.

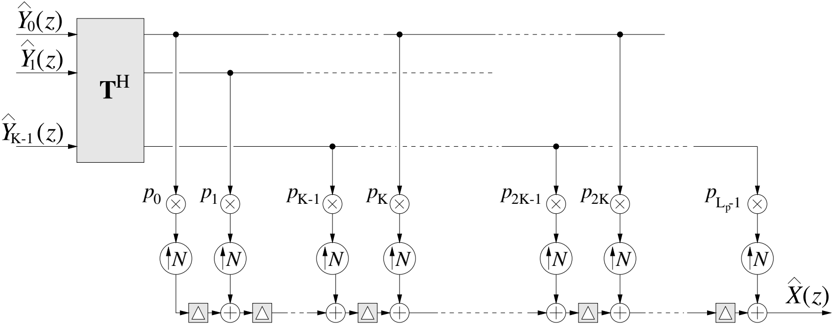
TVWS Transceiver — Filter Bank Implementation I

- Filter bank implementations can be low cost — nearly equivalent to the extraction of a single channel plus an FFT ...

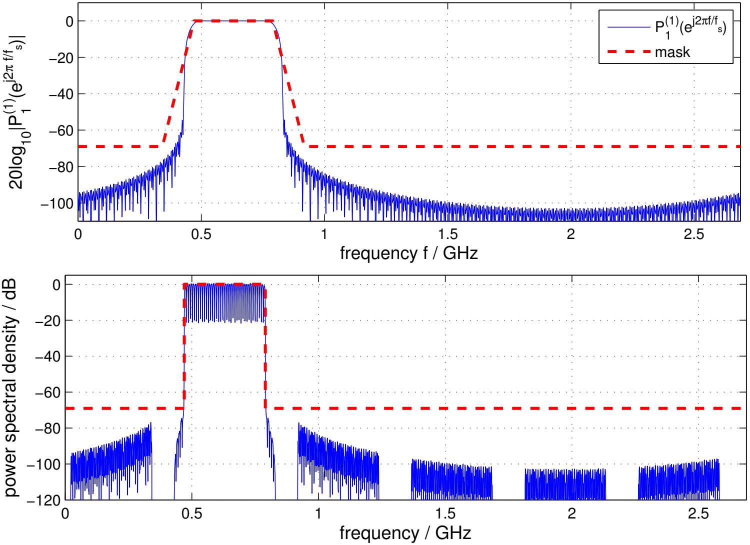


TVWS Transceiver — Filter Bank Implementation II

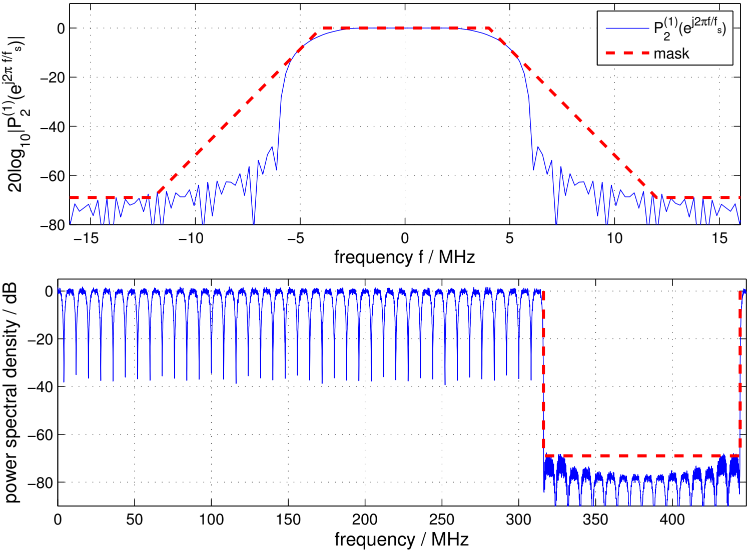
- Equivalent implementation for the receiver



Stage 1 Characteristics



Stage 2 Characteristics — RX



Filter Bank Cost . . .

- The total cost of on Tx or Rx implementation is given by

$$C^{(i)} = \left(L_1^{(i)} + \frac{L_2^{(i)}}{K_2^{(i)}} + 2\log_2 K_2^{(i)} + 1 \right) \frac{4 f_\mathrm{s}}{K_1^{(i)}}, \tag{1}$$

- we next compare this for the different design . . .

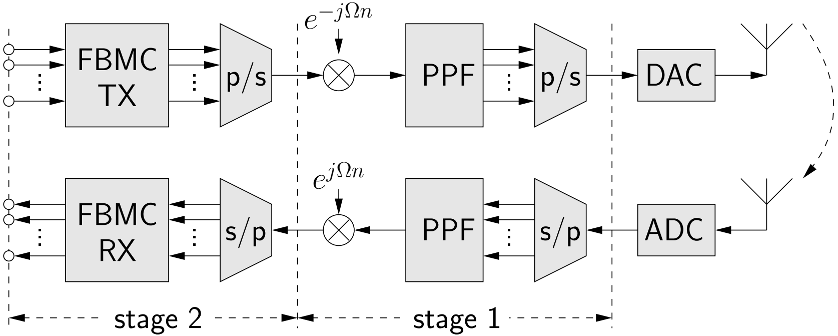
Filter Bank Parameters

- Bandwith reductions K_i for different receiver stages $i = 1, 2$ with associated increase in bit resolution ΔR_i, and other performance measures.

Design i		1	2	3
stage 1	$K_1^{(i)}$	6	7	8
	$\Delta R_1^{(i)}$	1.293	1.404	1.500
	$L_1^{(i)}$	120	200	400
stage 2	$K_2^{(i)}$	56	48	42
	$\Delta R_2^{(i)}$	2.904	2.793	2.696
	$L_2^{(i)}$	560	480	420
$C^{(i)}$ / GMAC/s		255.6	335.1	566.9
delay $\Delta^{(i)}$ / ms		5.86	4.32	3.36
reconstruction error / dB		-54.8	-55.7	-54.9
adjacent channel leakage / dB		-61.5	-63.1	-62.2
next-adj. channel leakage / dB		-72.2	-73.1	-72.8

TVWS Transceiver Summary

- Two-stage design with sampling at RF



- fixed point design has been considered
- influence of RF non-linearities and other detrimental influences must be investigated.

Conclusions

- A number of different technologies for Smart Grid Communications have been mentioned
- in a rural setting, not all of these are viable
- in particular, we have explored the use of wireless links in the UHF white space spectrum, where benign channel conditions allow non-line-of-sight and longer distance connections
- the availability of the white space spectrum coincides with low population densities
- low power, low cost, non-requirement of planning permission and possibility of community ownership make this an attractive technique
- situations similar to the Scottish Highlands and Islands exist elsewhere nationally (e.g. Wales and parts of England) and internationally
- while no tests have been performed explicitly in terms of smart grid applications, we believe that this technique can be a useful candidate.

TVWS For Smart Grid Communications

- TVWS is one chance to update communications infrastructure that is otherwise not economical to deploy
- TVWS might help to not just to realise broadband access in rural areas, but also provide an infrastructure for the increasing level of