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Enabling Rural Broadband Via TV "White Space"

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***Abstract*—The use of multiple frequency bands within a wireless network allows the advantages of each band to be exploited. In this paper we discuss how "HopScotch", a rural wireless broadband access test bed running in the Scottish Highlands and Islands, uses both 5 GHz and ultra high frequency "white space" bands to offer large data rates and expansive coverage whilst reducing the number of base stations or required transmission power. This reduction in energy consumption allows HopScotch to provide a low-cost and green solution for rural broadband delivery.**

I. Introduction

Sparsely populated rural areas suffer from a lack of affordable broadband access due the high infrastructure costs and low return on investment for telecommunications providers [1]. Fixed-point wireless access has been presented as a solution to the rural broadband problem [2]–[6] but in many cases the limited availability of frequency bands and the reliance on a power infrastructure limits the coverage of such low cost networks.

The choice of frequency bands used for transmission impacts on the potential coverage and capacity of a wireless network. The use of very high (VHF) or ultra high frequency (UHF) bands is addressed in [3], [4], [6]. Generally it is noted that the propagation characteristics are more benign in the UHF and VHF bands, where non-line of sight (LOS) links can be operated, compared to LOS-only transmission in the GHz range. Work in [3] and [6] follows a dual band approach using both UHF and WiMAX / WiFi bands in the 3.5 GHz and 5.2 GHz ranges to provide the best coverage to different population densities. A number of contributions have emerged that suggest the use of cognitive radio techniques within these bands to optimise throughput [7], [9].

Relying on transmission over benign propagation channels in combination with additional savings through the adaptation of code rate and modulation scheme to throughput requirements [10] enables the use of low-power green base-stations. As the RF power amplifier is the most power-hungry system component in the transmitter [8] a reduction in required transmission power leads to a reduction in power consumption. Such green base stations can rely solely on renewable energy sources therefore be independent of the electricity grid [6].

In this paper, we present a wireless rural broadband access network called "HopScotch" which is currently being trialled on the West coast of Scotland. It consists of point-to-point (PTP) and point-to-multi-point (PTMP) links which are similar to the WiFi network in [5], [11], but uses a "white space" UHF overlay for wider coverage and non-LOS links. With initial results of our system presented in [6], we here particularly focus on the different propagation characteristics in the UHF and GHz frequency bands, and the resulting advantages in realising and operating a low power rural broadband access network based on WiFi and UHF frequencies.

The paper is organised as follows. Sec. II introduces HopScotch and discusses the benefits and challenges of the HopScotch network communicating over both the 5 GHz and "TV white space" (TVWS) spectrum. The benefits of TVWS spectrum are explored in Sec. III. Sec. IV analyses how frequency selection impacts on the network and its green radio credentials. Finally, conclusions will be drawn in Sec. V.

II. HopScotch Frequency Use

Fig. 1 shows how "HopScotch" could connect a remote community to IP-backbone. PTP links create a network backbone between relay base stations, and PTMP links illuminate the community.

HopScotch uses standard IEEE 802.11n, operating in the 5 GHz spectrum for PTP links and to serve subscribers in close vicinity of the base station. The infrastructure additionally features an overlay TVWS network/testbed in a licensed UHF band, where a modified 802.11 protocol is utilised for transmission. A combination of spectral bands allow for an optimum trade-off between channel throughput and coverage for different scenarios. The use of licensed and unlicensed spectrum in the 5 GHz band allows off-the-shelf WiFi equipment to use a large channel bandwidth with high throughput. Employing TVWS frequencies enables greater base station coverage, especially in challenging radio terrain at the expense of a reduced channel bandwidth and throughput.

A. WiFi Wireless Lan Spectrum

Three frequency bands are available for outdoor use based on off-the-shelf IEEE 802.11abgn WiFi equipment in the UK,

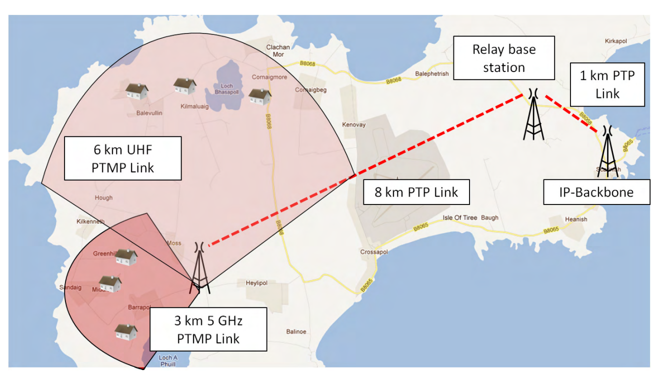

Fig. 1: Example of a HopScotch network connecting a remote community to IP-backbone.

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

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

as shown in Tab. I. The 5 GHz bands B and C are attractive for fixed rural broadband due to the transmit power limitations compared to 2.4 GHz. Band B is lightly licensed to allow a greater transmit power for fixed wireless links.

B. TV White Space Spectrum

The TV spectrum in Europe is divided into 8 MHz wide channels, ranging from 470 MHz (channel 21) to 862 MHz (channel 69). When in 2012 the UK's last analogue television signals will be switched over to digital terrestrial TV (DTT), 112 MHz of this band will remain vacant, freeing 14 UHF channels. Channels 36 and 69 will also be released. Reuse of interleaved bandwidths within the DTT range will be allowed by the UK's office for communications (Ofcom) as long as this will not interfere with a primary, licensed transmitter. The released spectrum together with any interleaved bandwidths available within the DTT range, is referred to as "white space". The availability of this spectrum depends on the geographical location and is generally higher in rural areas.

In the UK the available TVWS frequencies are likely to range between 470 MHz and 790 MHz with 8 MHz wide channels, for which Ofcom is currently formulating a policy for future use. In the US, the Federal Communications Commission (FCC) has already ruled on the use of TVWS frequencies in the US covering 54 MHz to 692 MHz with 6 MHz channels. For fixed devices the maximum allowed effective EIRP is 4 W in channels 2 to 51 (excluding 3,4 and 37) [12].

C. Link Selection and Trade-Offs

PTP links are created using the 5 GHz lightly licensed band-C (5.725-5.850 GHz) with maximum EIRP of 4 W. This 125 MHz spectrum is divided into two non-overlapping 40 MHz wide turbo channels, where each channel supports spatial multiplexing (i.e. 2x2 MIMO streams on vertical and horizontal polarisations). The resulting system with two independent spatial streams supports a theoretical data rate of 300 Mbps.

PTMP links use the unlicensed band-B (5.470–5.725 GHz) with a maximum EIRP of 1 W. The 255 MHz wide spectrum is divided into 11 non-overlapping 20 MHz or six 40 MHz channels. UHF links are primarily limited to a 5 MHz bandwidth to to fit within a TV channel.

III. Advantages of "White Space"

Wireless networks transmitting in the TVWS band have been estimated to cover four times the area that can be reached via current unlicensed bands in the 2.4 GHz and 5 GHz region, thus reducing the number of base stations required [13]. Contributing factors which are particularly relevant in rural environments are discussed below.

1) Free Space Path Loss : The transmission loss over a distance r is frequency dependent as the effective antenna aperture of a fixed gain antenna decreases with increasing frequency. When operating at two different transmission frequencies f_1 and f_2 for isotropic antennas with identical gains Frii's transmission equation [14] can be rearranged to

$$r_{(f_1)} = \left(\frac{f_2}{f_1}\right) r_{(f_2)} \quad , \tag{1}$$

in order to relate the distances $r_{(f_i)}$, $i = 1, 2$, over which an equivalent loss is experienced. Thus, given a fixed receive signal level, the propagation range at a lower frequency is greater than at a higher frequency [15]. According to (1), at 630 MHz (the middle frequency of the TVWS band) range is increased 9 times compared to 5.67 GHz (the middle frequency of 5 GHz bands B and C). Similarly the transmit powers required to receive the same power at the same distance when transmitting at frequencies f_i, $i = \{1, 2\}$ relate by

$$P_{t_{(f_1)}} = \left(\frac{f_2}{f_1}\right)^2 P_{t_{(f_2)}} \quad , \tag{2}$$

i.e. to transmit at 630 MHz requires 19.1 dB less power than transmitting at 5.67 GHz under the constraint of identical distances and receive powers.

2) Terrain Effects and Diffraction Loss : Point to point propagation path loss can be predicted under obstructive, non-LOS conditions between base station and terminal. As the size of the obstruction is much larger than the wavelength of the radio wave, knife-edge diffraction can be used to estimate the shadow loss [16]. The propagation loss L_{ke} due to knife edge diffraction as sketched in Fig. 2 can be estimated using the Fresnel diffraction parameter v. A good approximation is given by

$$v \approx = -h_p \sqrt{\frac{2(r_1 + r_2)}{(\lambda r_1 r_2)}} \quad , \tag{3}$$

with h_p the height difference between the virtual LOS between the transmit and receive antennas and the peak of the obstruction. The quantities r_1 and r_2 are measures of the distances between the edge, and the transmitter and receiver, respectively, as outlined in Fig. 2. Based on the wavelength λ of the carrier frequency, the propagation loss L_{ke} can then be calculated using Fresnel integrals [14].

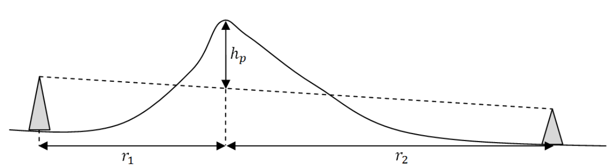

Fig. 2: Knife edge diffraction parameters.

As an example, over a 5 km link with a 30 m knife edge obstruction 900 m from the transmitter, the diffraction loss at 5.67 GHz is 9.4 dB higher than the estimated loss of 20.1 dB at 630 MHz.

3) Foliage : Studies have shown the attenuation due to vegetation to dependent on both frequency. Weissberger's mode predicts the propagation loss due to the presence of trees in a point to point link [17], with a path loss L_w

$$L_w = \begin{cases} 0.45\,(f)^{0.284}\,(d) & \text{, for } 0 \le d \le 14 \\ 1.33\,(f)^{0.284}\,(d)^{0.588} & \text{, for } 14 < d \le 400 \end{cases} \quad (4)$$

for a given frequency f [GHz] and a depth d [m] of foliage along the path.

As an example, using Weissberger's model for a foliage depth of 10 m the estimated propagation loss of 7.4 dB due to the foliage obstruction at 5.67 GHz is 3.4 dB higher than the loss experiences at 630 MHz.

IV. Impact of Frequency Band Selection

While most wireless rural broadband access systems rely on WiFi technologies in the 2.4 GHz and 5 GHz bands, HopScotch utilises a combination of 5 GHz WiFi and UHF frequency bands for transmission. Therefore, using an example comminity we analyse how the use of UHF TVWS bands can reduce the burden on base station coverage and transmit power requirements, compared to transmission at 5 GHz. This allows households situated further away from the community hub to be reached using fewer base stations or a lower transmit power.

A. Base Station Placement

An example community of six households (labelled A to F) for "HopScotch" is shown in Fig. 3. The optimum base station placement to serve this community can be determined using the Radio Mobile planning tool for a base station height of 10 m and a maximum permitted transmit power of 1 W EIRP for 5 GHz band-B transmissions. Radio Mobile uses the Longley-Rice propagation model for non-LOS links and the two-ray path model for LOS links [14]. The effects of foliage and other clutter have been ignored for this study. When using 5 GHz band-B, no single base station can cover all six nodes given a minimum received signal strength of -85 dBm, the minimum receive signal strength observed during trial tests to maintain a reasonable connection. At TVWS frequencies (630 MHz for this analysis) two locations allow coverage of all six nodes as shown by the red shading in Fig. 3.

Whilst no single base station using 5 GHz bands can serve the community at 1 W EIRP, coverage for the entire community can be achieved by introducing two communicating base stations as shown in Fig. 4. Base station A (BSA) can serve nodes C, D, E and F with omnidirectional coverage and base station B (BSB) can serve nodes A and B.

Using a combination of 5 GHz and UHF frequencies for this scenario allows the available data rate to be maximized for each user using only one base station. Base station A (BSA) can serve users C, D, E and F at 5 GHz, providing a greater bandwidth and hence data rate for users. A white space overlay on BSA also allows it to service users A and B without the need for an additional base station.

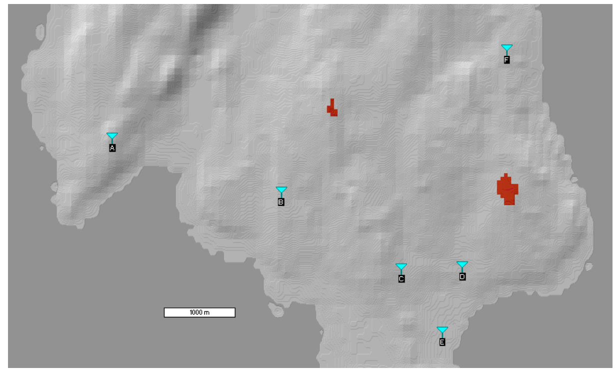

Fig. 3: Example community with areas for a potential base station to provide coverage at 630 MHz at 1 W EIRP.

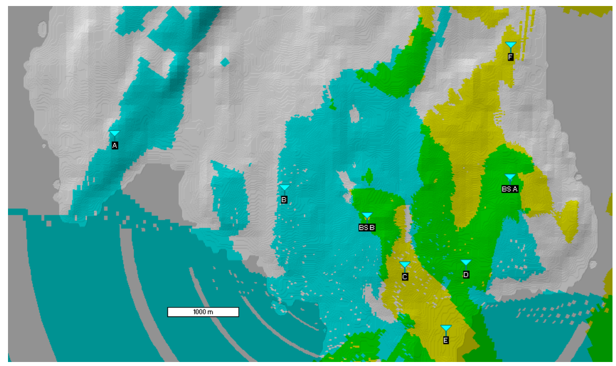

Fig. 4: Coverage provided by two base stations at 5660 MHz 1 W EIRP, with yellow shading representing coverage provided by base station A (BSA), blue shading representing the coverage provided by base station B (BSB), and the overlapping coverage indicated by green shading.

B. Link Transmission Power

An alternative to adding additional base stations at 5 GHz to cover all nodes is to increase the transmit power above 1 W EIRP. This may be possible in some regulatory environments. To demonstrate the required transmission power one long non-LOS and one short LOS link are considered; between base station BSA and users A and D. The link elevation profiles are shown in Fig. 5. The expected received signal power P_{Rx} in decibels for a given transmission power P_{Tx}, transmit and receive antenna gains (G_{Tx}, G_{Rx}) line losses (L_{Tx}, L_{Rx}) and path loss L_{PL} is given by:

$$P_{Rx} = P_{Tx} + G_{TX} - L_{TX} - L_{PL} + G_{Rx} - L_{Rx} \quad (5)$$

Similarly for a given receive power the required transmit power in decibels can be calculated:

$$P_{Tx} = P_{Rx} - G_{Tx} + L_{Tx} + L_{PL} - G_{Rx} + L_{Rx} \quad (6)$$

Using (5) and (6), Tab. II shows the simulated path loss between base station BSA and users A and D and the expected receive power given a transmit and receive antenna gain of 14 dBi, line losses of 0.5 dB and an EIRP of 1 W. The required transmission power to create a link with a received signal strength of -85 dBm is also calculated. To create a

(a)

(b)

Fig. 5: Terrain profiles showing elevation between base station A (BSA) and (a) node A and (b) node D.

link between base station BSA and user A a substantial EIRP and therefore transmission power would be required in the 5 GHz band which is not permitted in the UK and is detrimental for a renewable powered system due to increased power consumption.

Tab. II also contains expected link performance at UHF frequencies using the same system parameters. A substantial reduction in path loss is expected at UHF frequencies compared to 5 GHz, especially in the longer non-LOS link. Therefore when using a UHF link, the propagation characteristics allow a reduction in transmit power or an increase in receive power compared to the 5 GHz band, reducing power consumption in the power amplifier or improving user throughputs by allowing higher order modulation schemes and code rate to be used. As each link is fixed the transmission power can be set during installation using channel measurements to achieve the desired receive signal strength.

V. Conclusion

We have discussed the differences in propagation between “white space” UHF and 5.2 GHz WiFi bands, and the resulting impact on transmission gains, influenced by factors such as distance, foliage, LOS/non-LOS conditions etc. Using UHF bands presents the opportunity for either wider coverage areas by increasing the distance between base station and receiver, or to drop the transmit power. Thus, rural broadband access networks such as HopScotch can rely on a lower density of basestations and operate with a lower power budget, enabling the use of renewables in autonomous base stations. This may be sufficient to provide incentives to realise rural broadband access in remote and sparsely populated areas.

Node	**A @ 630 MHz**	**A @ 5660 MHz**	**D @ 630 MHz**	**D @ 5660 MHz**
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 Rx Level	5.8 dBm	32.6 dBm	-14.8 dBm	2.6 dBm

TABLE II: Link calculations and transmit and receive powers between the base station and nodes A and D.

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