Centre for White Space Communications

In-Home TVWS Measurements Using IEEE 802.11af

Version 1.1

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Contents

Foreword

Mediatek would like to thank the Centre for White Space Communications at the University of Strathclyde for the opportunity to collaborate within the Glasgow pilot on the testing of our prototype tri-band 802.11af/802.11n radios. Mediatek is very happy to endorse the results of the test programme presented in this report. The results obtained within four dwellings of different construction point towards some of the coverage and throughput gains that are achievable with our 802.11af technology, and we would like to welcome this first step towards the real world application of this exciting development for opportunistic use of spectrum.

MediaTek, Inc.

Executive Summary

This report describes in-home TV White Space (TVWS) measurements that were made by the Centre for White Space Communications (CWSC)[1] in June 2014, with support from MediaTek, 6harmonics, and Sky. The measurements used prototype IEEE 802.11af equipment from MediaTek, and comparisons were made with IEEE 802.11n production equipment operating in the 2.4 GHz and 5 GHz bands.

The use of TV white space (TVWS) spectrum represents a new approach to managing spectrum, with significant potential for improving overall spectral efficiency and encouraging new applications and business models to emerge. One potential application is the improvement of the wireless broadband access delivered today by 'Wi-Fi' using the 2.4 GHz ISM band and the 5 GHz UNII bands. The IEEE has recently ratified the IEEE 802.11af standard, which adds the TVWS bands to the IEEE 802.11 family of specifications, thereby securing the possibility of mass market adoption. This has relevance for ISPs, which could potentially benefit from the improved range and bandwidth that is expected from TVWS.

CWSC has been working with MediaTek and 6harmonics, who agreed to provide CWSC with access to their prototype IEEE 802.11af radios (which also incorporate 802.11n), along with engineering support, for carrying out the tests described here, and with Sky, who offered practical assistance with test locations. The measurements were made in four homes in the Glasgow area. The homes comprised a mix of construction types: older-style properties with outer walls made of sandstone and internal walls made of brick, and more modern-style properties with an outer frame made of timber and brick and internal walls made of plasterboard.

A key aim was to compare the performance of IEEE 802.11af (TVWS) and IEEE 802.11n (in both the 2.4 GHz band and the 5 GHz band) in a typical home-based set-up. The basic methodology therefore involved visiting a small number of homes, setting up a base station/access point at a suitable location in each home, and measuring coverage and throughput performance when connected to a client station which was placed at various locations in and around the home. This was done for each of the three technologies under test, i.e. IEEE 802.11af, IEEE 802.11n at 2.4 GHz, and IEEE 802.11n at 5 GHz.

The results indicate that IEEE 802.11af has significant potential to complement IEEE 802.11n, adding increased in-home coverage capabilities which will complement the capabilities of IEEE 802.11n. MediaTek is planning to make samples of its tri-band Wi-Fi IC product available to customers in Q4, 2015. The device will support IEEE 802.11af in TVWS as well as IEEE 802.11n at 2.4 GHz and 5 GHz, thus providing a range of complementary features and capabilities which Wi-Fi devices may exploit for optimal performance in different situations and circumstances.

[1] The Centre for White Space Communications was set up by the University of Strathclyde in March 2011 with seed funding from the Scottish Funding Council.

1 INTRODUCTION

The use of TV white space (TVWS) spectrum represents a new approach to managing spectrum, with significant potential for improving overall spectral efficiency and encouraging new applications and business models to emerge. The concept is steadily gaining momentum throughout the world, and Ofcom, the UK's communications regulator, is currently running a pilot to test and validate its draft framework for managing access to TVWS spectrum.

As part of the Ofcom pilot, the Centre for White Space Communications (CWSC)[1] is running pilot activities in Glasgow, with support from the Scottish Government, Microsoft, Sky, and others. The project aims to assist Ofcom in its efforts to progress towards full regulations being put in place and also to demonstrate some of the benefits and opportunities associated with licence-exempt access to TVWS spectrum.

One potential application is improvements to the mobile broadband service delivered today by 'Wi-Fi' in the 2.4 GHz ISM band and the 5 GHz UNII bands. Almost invariably these days, it is a Wi-Fi enabled router that sits at the end of the ISP's copper, coax or fibre cable to domestic dwellings and small businesses while many Internet Service Providers (ISPs) also deploy Wi-Fi hot spots to deliver public broadband in many locations.

In recognition of the fast rising demand for mobile data consumption, Ofcom acknowledges in its WRC2015 consultation[2] that there needs to be a significant increase in the spectrum available for mobile broadband. In the same consultation the possibility of designating the bands from 5.350 – 5.470 and 5.725 – 5.925 as extensions to the UNII Wi-Fi bands is discussed and it appears that this will take some time to progress because of the need to carry out more sharing studies. It would therefore appear that expansion of spectrum available for Wi-Fi will lag behind that being made available for IMT (mobile telecommunication networks) in 800 MHz, 700 MHz, 2.6 GHz, 3.4 GHz, and other bands.

TVWS in UHF offers an opportunity to obtain more spectrum locally for applications which are the same or similar to those supported by Wi-Fi. The IEEE has recently ratified the IEEE 802.11af standard, which adds TVWS features to the IEEE 802.11 family of specifications, thereby securing the possibility of mass market adoption. This has relevance for ISPs, which could potentially benefit from the improved range and bandwidth that is expected from TVWS.

With this in mind, CWSC engaged with several parties to investigate the performance of IEEE 802.11af in a small number of homes in the Glasgow area, and to carry out a comparison of IEEE 802.11af, Wi-Fi at 2.4 GHz, and Wi-Fi at 5 GHz. In particular, CWSC has been working with MediaTek and 6harmonics, who agreed to provide CWSC with access to their prototype IEEE 802.11af radios, along with engineering support, for carrying out these tests, and with Sky, who offered practical assistance with test locations.

This report provides a description of the tests that were carried out and the results that were obtained.

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[1] The Centre for White Space Communications was set up by the University of Strathclyde in March 2011 with seed funding from the Scottish Funding Council.

[2] http://stakeholders.ofcom.org.uk/consultations/wrc15/

2 PROTOTYPE 802.11af RADIOS

MediaTek's prototype IEEE 802.11af radios are 1×1 FPGA-based systems with support for Long Guard Intervals. At the time of the tests described in this report, MediaTek had two versions of firmware:

1. Medium performance firmware, which was used for the in-home tests for reasons of stability;
2. Higher performance firmware which was capable of delivering higher peak throughput rates, but was less stable than the medium performance firmware.

For the tests described in this report, the more stable, medium performance firmware was used. Figure 2-1 shows UDP throughput figures for the medium performance firmware, as measured in the laboratory.

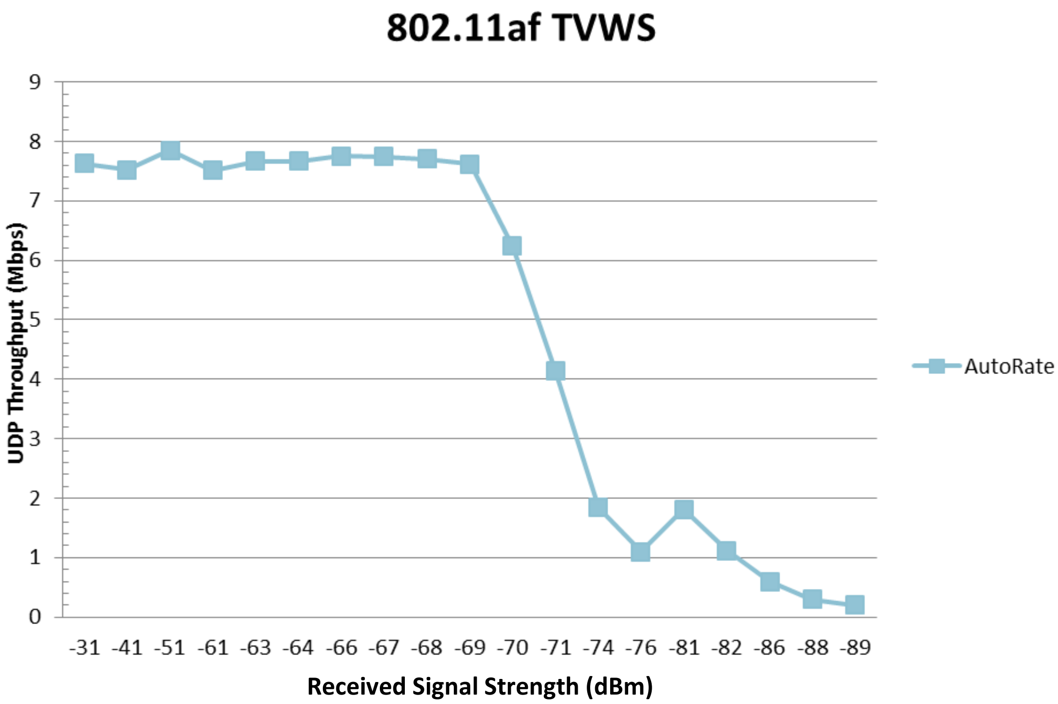

Figure 2-1: UDP throughput figures for medium performance firmware, using automatic MCS selection (AutoRate).

The higher performance firmware is still under development, and its stability will improve in the future. It is capable of supporting data throughput rates of up to 25 Mbps (UDP) and 20 Mbps (TCP). Further details are given in Appendix 7A.

3 TEST METHODOLOGY

A key aim was to compare the performance of IEEE 802.11af (TVWS) and IEEE 802.11n (in both the 2.4 GHz band and the 5 GHz band) in a typical home-based set-up. The basic methodology therefore involved visiting a small number of homes, setting up a base station/access point at a suitable location in each home, and measuring coverage and throughput performance when connected to a client station which was placed at various locations in and around the home. This was done for each of the three technologies under test, i.e. IEEE 802.11af, IEEE 802.11n at 2.4 GHz, and IEEE 802.11n at 5 GHz.

CWSC has a non-operational development licence, issued by Ofcom, which allows TVWS radios to be operated in Ch34, Ch35, and/or Ch37 with an EIRP of up to 36 dBm (4 W). The licence allows TVWS base stations to be located anywhere within 10 km of the Royal College Building in the centre of the city, which effectively meant that the homes used for the tests had to be within this geographical area.

3.1 Test Homes

It was desired that a mix of older homes and modern homes would be used in the tests. Older buildings tend to have solid internal walls that are made of brick or stone, while more modern homes tend to have internal walls that are constructed using a timber frame covered with plasterboard, which, in some cases, may be foil-backed. It was expected, therefore, that the radio propagation characteristics would depend on the type of building in which the tests were being carried out; hence the desire for a mix of building types.

Four homes were selected and used:

1. Two tenement flats, with outer walls made from sandstone and internal walls made from brick (Locations 1 and 2 in Figure 3-1);
2. A large, three-storey house constructed some 100 years ago, with outer walls made from sandstone up to 60 cm thick in some places and internal walls made from brick (Location 3 in Figure 3-1);
3. A modern, two-storey home constructed 10-15 years ago, with outer walls made from brick and internal walls made from timber and plasterboard (Location 4 in Figure 3-1).

The Royal College Building (Location 0 in Figure 3-1) was used for initial set-up and testing prior to visiting the homes. This is a large building with thick sandstone walls.

3.2 Performance Measurements

Within each home, the performance of each radio technology was measured using three different but related methods:

1. *RF signal coverage*:
   The base station was set up to continuously transmit data to the client, and the received signal strength was measured at the client location.
2. *Data throughput rate*:
   The base station was set up to continuously transmit data to the client, and the maximum data throughput rate was measured for both TCP and UDP.

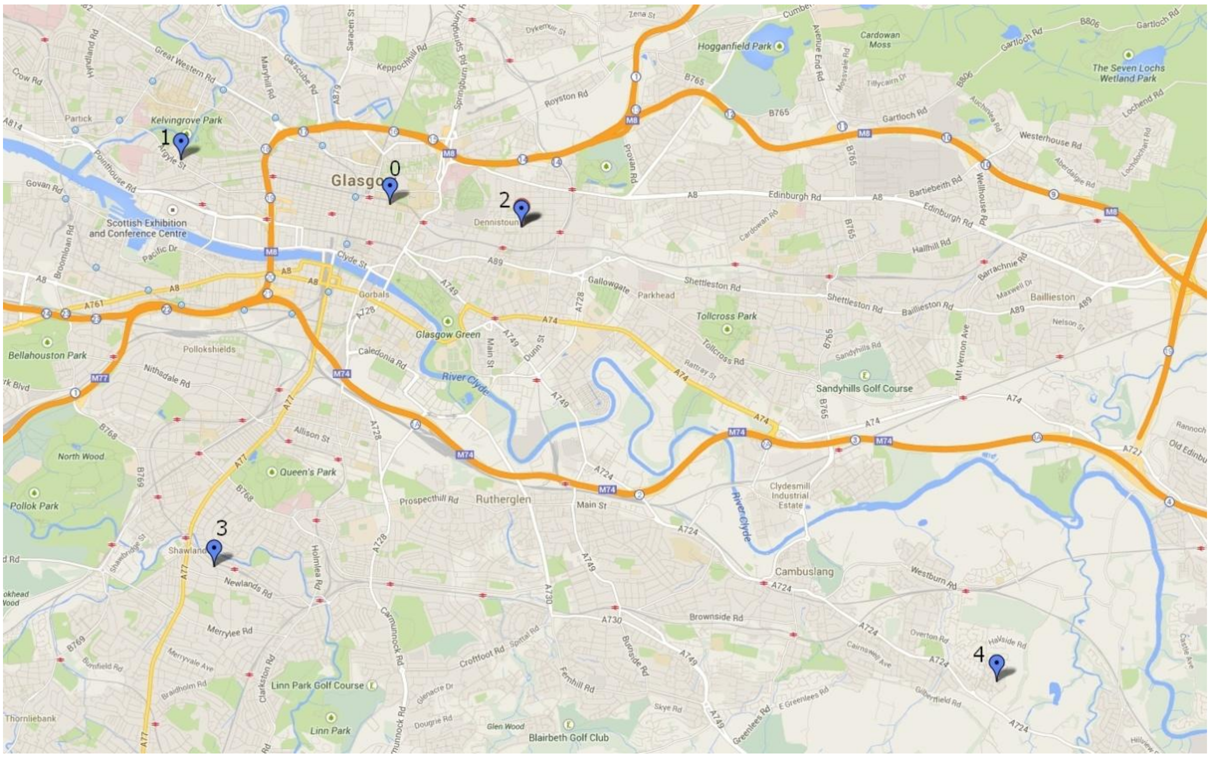

Figure 3-1: *Locations of homes used for the tests. (Location 0 is the Royal College Building.)*

3. *HD video streaming*:
   A 3-minute 1080p HD video provided by Sky was transmitted from the base station to the client, and the quality was observed.[1]

3.3 TV-Band Spectrum Usage

A key issue for any application that wishes to make use of TVWS spectrum in a particular geographical location is the availability of white space spectrum in that location. When the full UK regulations are put in place, Ofcom will require master white space devices to consult a qualified database to determine the maximum power level at which they may transmit in each channel.

At the time of the tests being discussed here, the database parameters for Glasgow were still being developed, and the tests were therefore carried out using CWSC's non-operational development licence. Nevertheless, it was deemed useful to have an idea of spectrum usage in the TV band in the location of each home, so this formed a part of the measurements that were made. Specifically, a hand-held spectrum analyser was used to measure spectrum usage within the range 470-790 MHz (Ch21 – Ch60). This gives a rough indication of how much usable white space spectrum might be available, although it should be borne in mind that the Ofcom-approved database will be the ultimate authority on this.

[1] The video content was encoded at 10 Mbit/s, but it actually required a radio link that could support at least 15 Mbit/s UDP (typically requiring at least MCS-5) in order to successfully transmit and receive the video. In practice, it proved difficult to obtain such a link in the homes; this will be discussed further in Section 4.

3.4 Radio Configuration

In order to perform 'fair' comparisons between IEEE 802.11af and IEEE 802.11n, attempts were made to configure the radios as similarly as possible. In particular, the following configuration parameters were given attention:

- **Transmit Power**
  The transmit power of MediaTek's prototype 802.11af radios was limited to a maximum of 18 dBm, so the 802.11n access point was configured to transmit at 18 dBm as well.

- **Bandwidth**
  IEEE 802.11n radios can operate with a spectral bandwidth of 20 MHz or 40 MHz, while MediaTek's prototype IEEE 802.11af radios operate within one TV channel, with a maximum bandwidth of 8 MHz. This gives the IEEE 802.11n radio a potential advantage in terms of achievable data throughput, and it is desirable, therefore, that the radios should all use the same bandwidth if efficiency is a criterion that is to be compared. However, the IEEE 802.11n radio that was used in the tests had no mechanism by which the bandwidth could be manually configured to anything other than 20 MHz or 40 MHz. For the tests, it was configured to use a bandwidth of 20 MHz.

- **Antennas**
  The IEEE 802.11n radio used in the tests has six built-in antennas with gains of 5 dBi for those three which operate at 2.4 GHz and 7 dBi for those three which operate at 5 GHz. The unit has no support for the connection of external antennas, so using the built-in antennas was the only option. For the IEEE 802.11af radio, a DAM-P9-P-R2-003-22-03 omnidirectional antenna with a gain of about 1 dBi was used. (This was deemed to be reasonably representative of the characteristics of a typical antenna for home-consumer applications.) Ideally, the transmit powers of the radios should be adjusted to take account of the gains of the antennas that were being used, which implies that the transmit power of the 802.11n access point should be reduced by about 4 dB for operation in the 2.4 GHz band and by about 6 dB for operation in the 5 GHz band. However, this was not done, and the results are presented 'as is', with all radios configured to transmit at 18 dBm.

- **MIMO**
  The IEEE 802.11n unit is capable of operating in 3×3 MIMO mode in each of the 2.4 GHz and 5 GHz bands, and this is automatically managed with no opportunity for manual configuration. It is likely that IEEE 802.11af radios will, in the future, support MIMO operation, but the IEEE 802.11af radio used for the tests is a SISO system (1×1), so it was deemed desirable that the IEEE 802.11n radios should also operate in a SISO mode. Given 802.11n access point's lack of manual configurability options, it was decided that it would be opened up and certain antennas physically disconnected in order to force SISO operation.[1]

With the radios configured as described above, the intention was to make the IEEE 802.11n and IEEE 802.11af radios operate in a similar a manner as was practicably possible, although it should be noted that this aim was achieved only partly.

It is also worth noting that the decision to try to make the radios operate as similarly as possible was justified on the basis that the aim of the tests was to compare the performance of the two radio

[1] This created a 1×1 system; however, the effect on the processing algorithms within the radio was not investigated.

technologies, which requires things such as transmit power and bandwidth to be equal (or results normalized in some way). The fact that IEEE 802.11n has more bandwidth available for use gives it an advantage over the current IEEE 802.11af radios, but it is widely expected that future versions of IEEE 802.11af radios will be capable of bonding multiple 8 MHz TV channels together when available, thereby making use of greater bandwidth.

4 TEST RESULTS

In this section, measurement results for each of the four test homes are presented. Coverage and data throughput test are presented first, followed by signal strength measurements made in the TV band (470-790 MHz) at each of the homes.

4.1 Coverage and Throughput Tests

Coverage and throughput performance were measured in each of the four test homes for each of the three technologies.

4.1.1 Home 1

Home 1 (shown in Figure 4-1) is a 1st floor tenement flat with sandstone external walls and brick internal walls. The floor plan and test point locations are shown in Figure 4-2. The base stations (access points) were initially placed in the hallway next to the BT telephone socket (at the yellow-coloured point marked 'WIFI AP' and the orange-coloured point marked 'TVWS AP') and performance measurements were made with client devices at Locations 1, 2, and 4. The base stations were then moved to the turquoise-coloured point marked 'WIFI AP' and the green-coloured point marked 'TVWS AP' and performance measurements were made with client devices at Location 3.

Figure 4-1: Home 1 as viewed from the street at the front of the building.

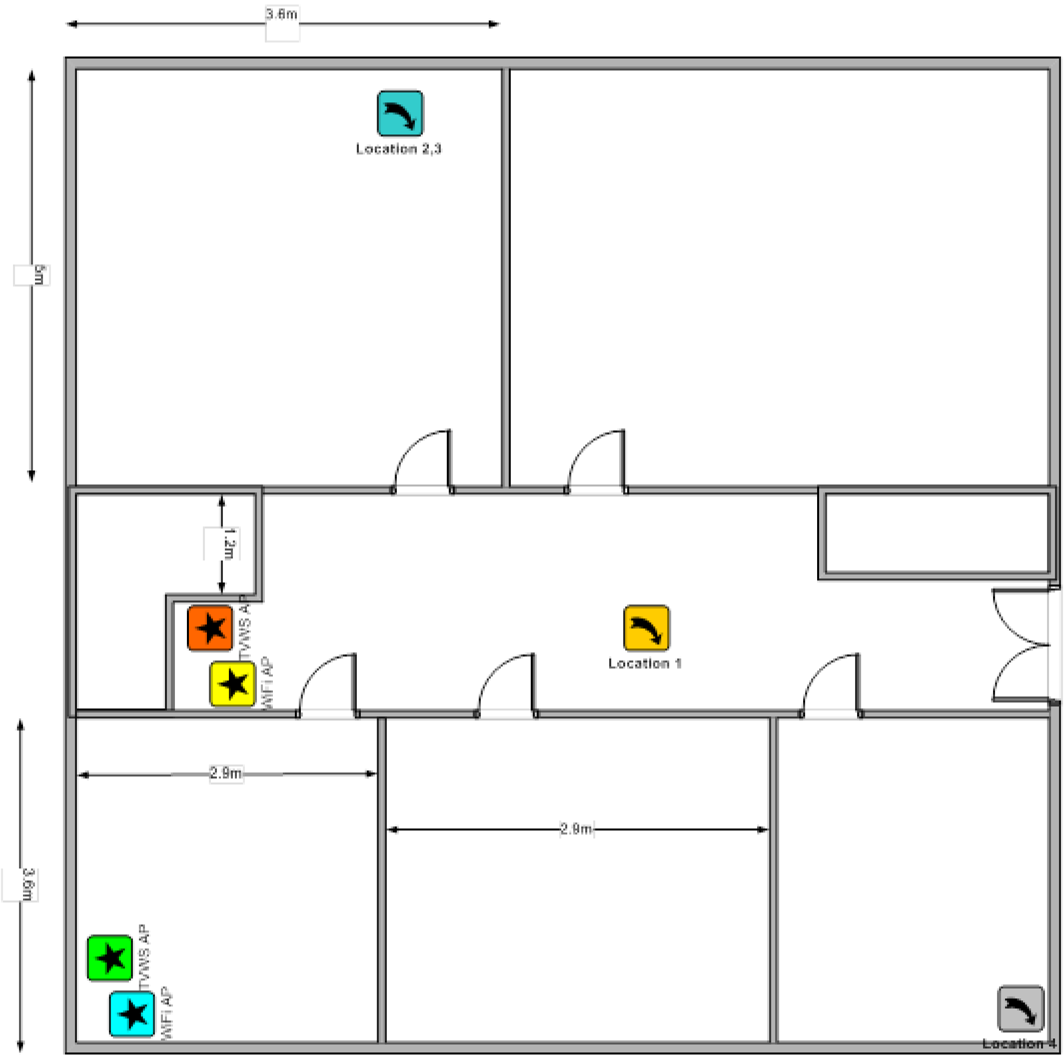

Figure 4-2: Floor plan for Home 1.

The performance results measured in Home 1 are shown in Table 4-1 and are shown graphically in Figure 4-3.

		Home 1						
		Tx Power (dBm)	Chan B/W (MHz)	Received Power (dBm)		Throughput (iperf)		Comment (if applicable)
				Spectrum Analyser	RSSI	TCP (Mbit/s)	UDP (Mbit/s)	
Loc'n 1	802.11af	18	8	-40	-30	10	15	Good Sky video quality
	802.11n (2.4 GHz)	18	20	–	-56	30	40	Good Sky video quality
	802.11n (5 GHz)	18	20	–	-54	30	40	Good Sky video quality
Loc'n 2	802.11af	18	8	-53	-45	10.1	12	
	802.11n (2.4 GHz)	18	20	-86	-67	24	25	
	802.11n (5 GHz)	18	20	Noise Floor	-77	–	–	Unable to establish connection
Loc'n 4	802.11af	18	8	-65	-60	5	6.12	
	802.11n (2.4 GHz)	18	20	-85	-79	1.46	?	There was an unexplained issue with the functionality of the UDP link during this measurement.
	802.11n (5 GHz)	18	20	Noise Floor	Noise Floor	–	–	Unable to establish connection
Loc'n 3	802.11af	18	8	-58	-58	8.93	11.3	
	802.11n (2.4 GHz)	18	20	-86	-81	11	?	There was an unexplained issue with the functionality of the UDP link during this measurement.
	802.11n (5 GHz)	18	20	-97	-87	–	–	Unable to establish connection

Table 4-1: Performance results measured in Home 1.

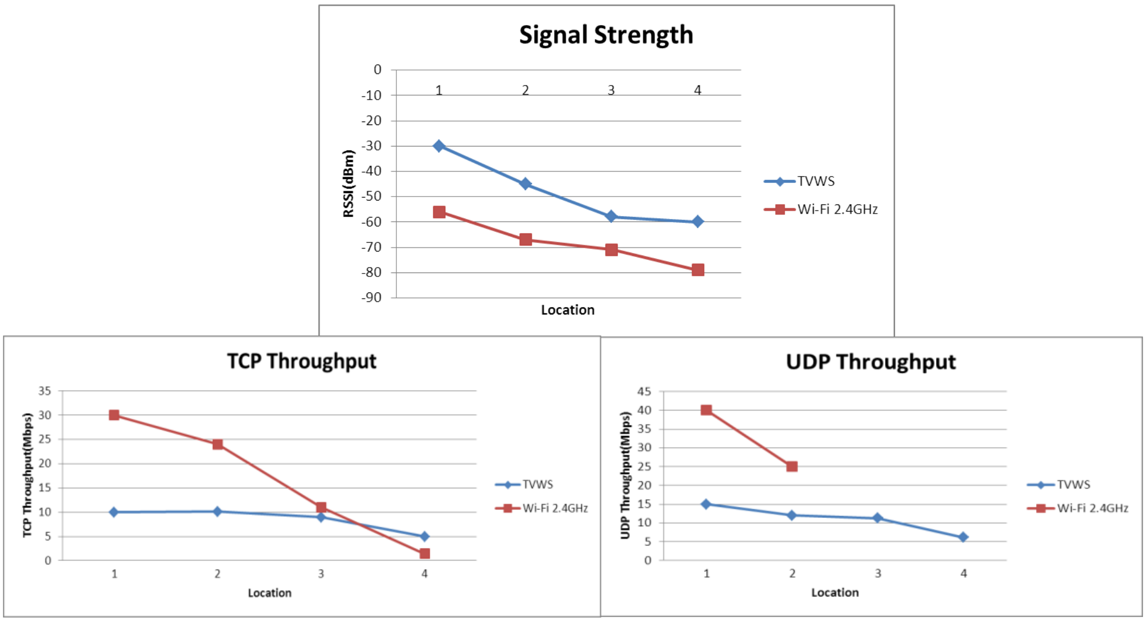

Figure 4-3: Graphed performance measurements for Home 1.

4.1.2 Home 2

Home 2 (shown in Figure 4-4) is, like Home 1, a 1st floor tenement flat with sandstone external walls and brick internal walls. The floor plan and test point locations are shown in Figure 4-5. The base stations (access points) were placed in the hallway as this was deemed to be the place that would 'naturally' be chosen by the home-owner, even though the BT telephone socket was located next to the kitchen window where the telephone cables entered the premises. Performance measurements were made with client devices at Locations 1, 2, and 3. It should be noted that Location 3 is in the garden at the back of the premises, and this was chosen because the owner has hitherto been unable to establish Wi-Fi connectivity while sitting in the garden area.

Figure 4-4: Home 2 as viewed from the street at the front of the building.

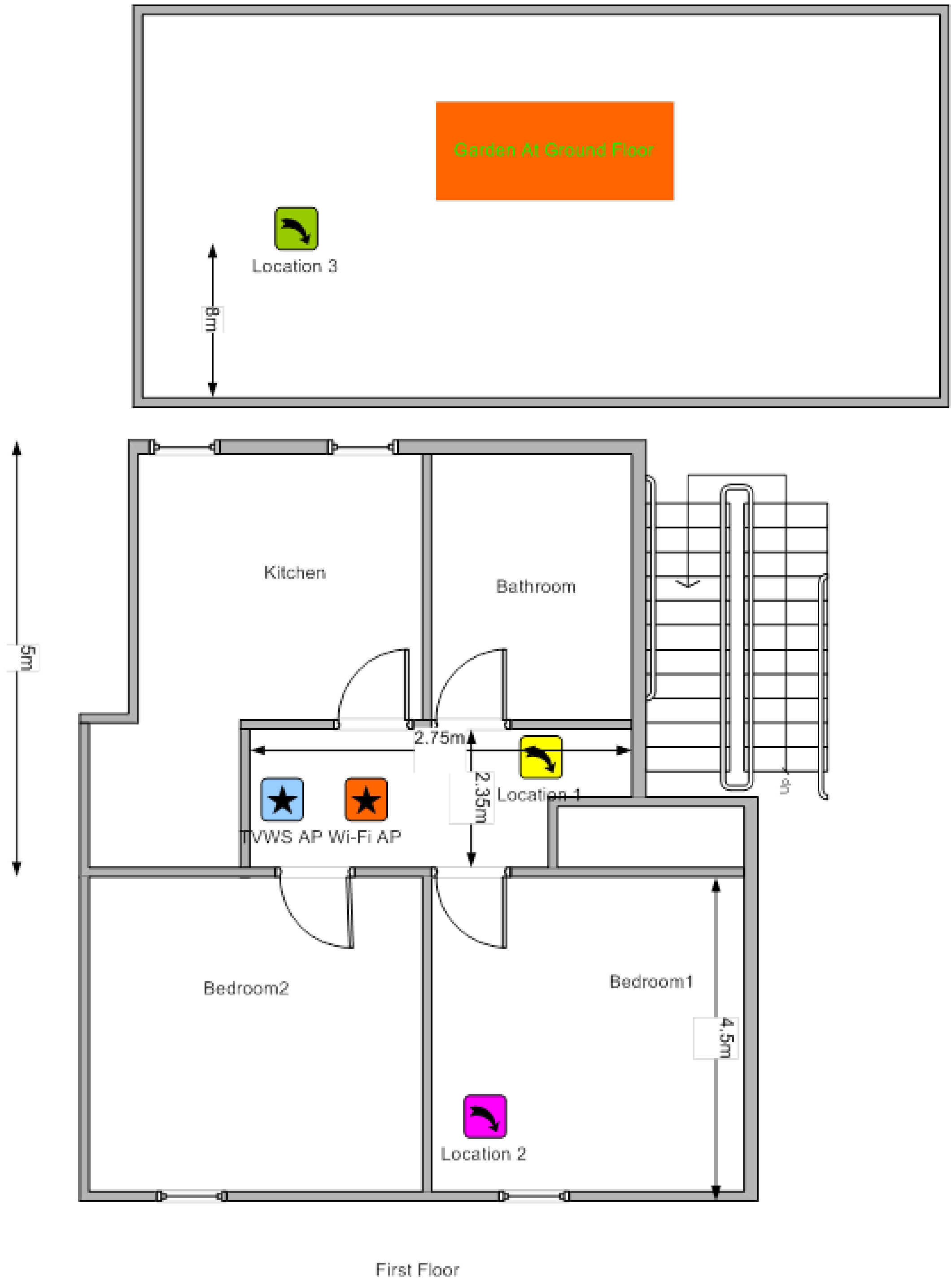

Figure 4-5: Floor plan for Home 2.

The performance results measured in Home 2 are shown in Table 4-2 and are shown graphically in Figure 4-6.

		Home 2						
		Tx Power (dBm)	Chan B/W (MHz)	Received Power (dBm)		Throughput (iperf)		Comment (if applicable)
				Spectrum Analyser	RSSI	TCP (Mbit/s)	UDP (Mbit/s)	
Loc'n 1	802.11af	18	8	-40	-30	10	15	Good Sky video quality
	802.11n (2.4 GHz)	18	20	–	-56	33	40	Good Sky video quality
	802.11n (5 GHz)	18	20	–	-54	30	40	Good Sky video quality
Loc'n 2	802.11af	18	8	-58	-48	9.4	14	
	802.11n (2.4 GHz)	18	20	-70	-69	33	40	
	802.11n (5 GHz)	18	20	Noise Floor	Noise Floor	–	–	Unable to establish connection
Loc'n 3	802.11af	18	8	-69	-60	8.34	14.6	
	802.11n (2.4 GHz)	18	20	Noise Floor	-93	–	–	Unable to establish connection
	802.11n (5 GHz)	18	20	Noise Floor	Noise Floor	–	–	Unable to establish connection

Table 4-2: Performance results measured in Home 2.

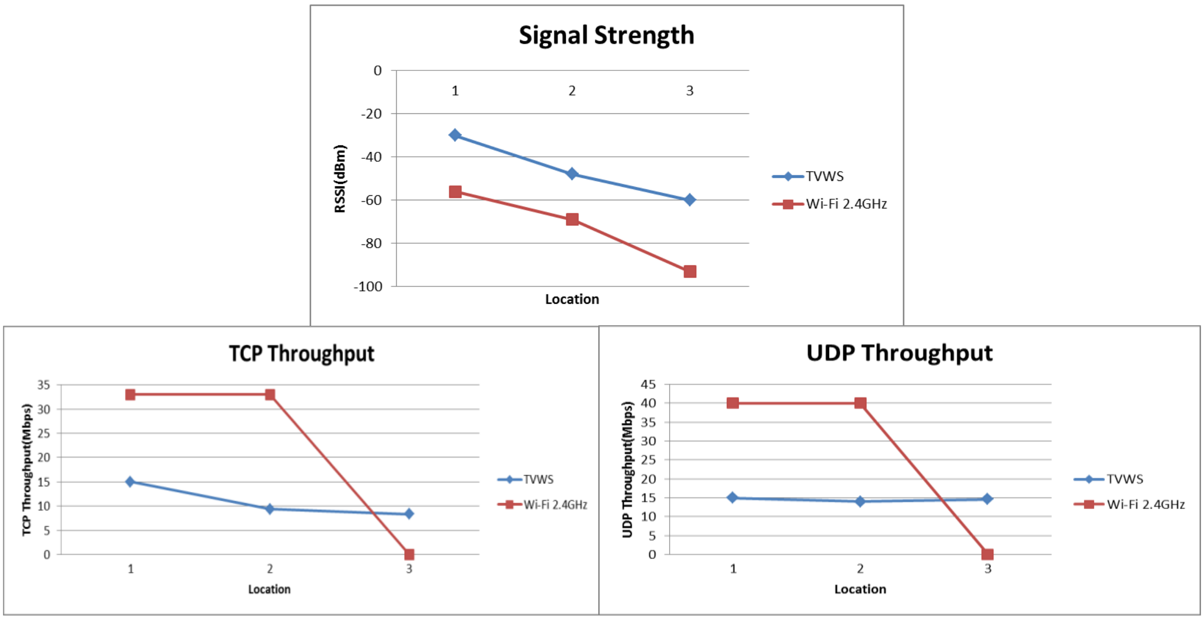

Figure 4-6: Graphed performance measurements for Home 2.

4.1.3 Home 3

Home 3 (shown in Figure 4-7) is a large, three-storey house constructed some 100 years ago, with outer walls made from sandstone up to 60 cm thick in some places and internal walls made from brick. The floor plan and test point locations are shown in Figure 4-8. The base stations (access points) were placed in the hallway, just inside the front door of the house, as this was where the BT telephone socket was located. Performance measurements were made with client devices at Locations 1, 2, and 3. It should be noted that Location 3 is in an outdoor yoga hut, and this was chosen because the owner has hitherto been unable to establish Wi-Fi connectivity in this location.

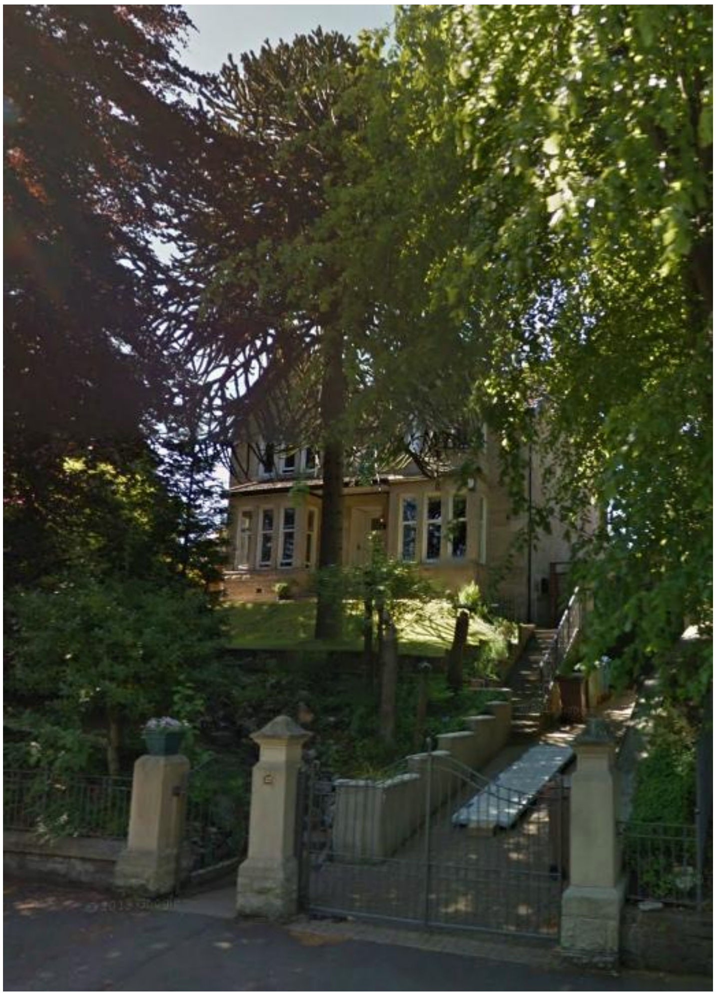

Figure 4-7: Home 3 as viewed from the street at the front of the house.

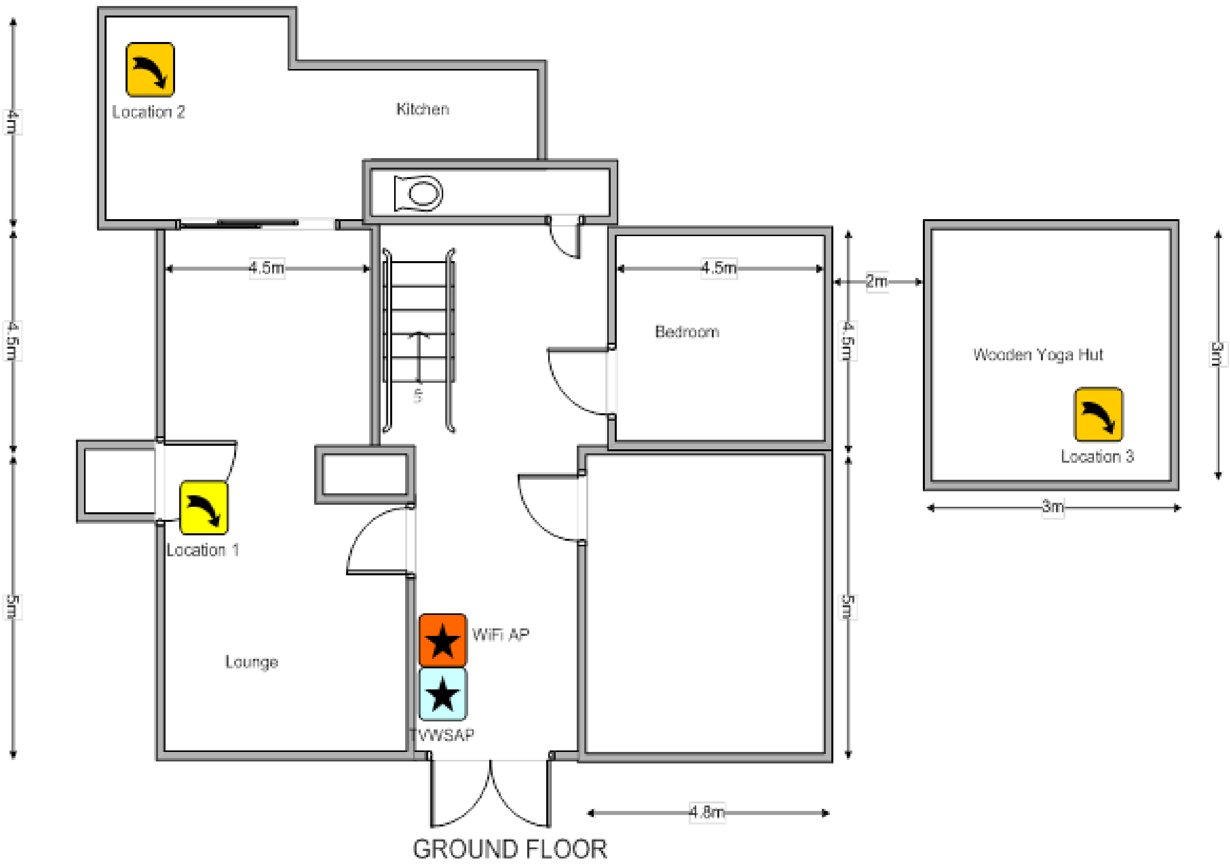

Figure 4-8: Floor plan for Home 3.

The performance results measured in Home 3 are shown in Table 4-3 and are shown graphically in Figure 4-9.

		Home 3						
		Tx Power (dBm)	Chan B/W (MHz)	Received Power (dBm)		Throughput (iperf)		Comment (if applicable)
				Spectrum Analyser	RSSI	TCP (Mbit/s)	UDP (Mbit/s)	
Loc'n 1	802.11af	18	8	-73	-42	4.83	9.43	Unable to stream Sky video
	802.11n (2.4 GHz)	18	20	-81	-71	0.6	1.69	Unable to stream Sky video
	802.11n (5 GHz)	18	20	Noise Floor	-81	–	–	Unable to establish connection
Loc'n 2	802.11af	18	8	-78	-60	0.835	0.968	
	802.11n (2.4 GHz)	18	20	-88	-93	–	0.36	Only barely able to maintain connection
	802.11n (5 GHz)	18	20	Noise Floor	Noise Floor	–	–	Unable to establish connection
Loc'n 3	802.11af	18	8	-80	-61	1.4	–	Yoga Hut – very patchy coverage
	802.11n (2.4 GHz)	18	20	-97	-110	–	–	Unable to establish connection
	802.11n (5 GHz)	18	20	-89	Noise Floor	–	–	Unable to establish connection

Table 4-3: Performance results measured in Home 3.

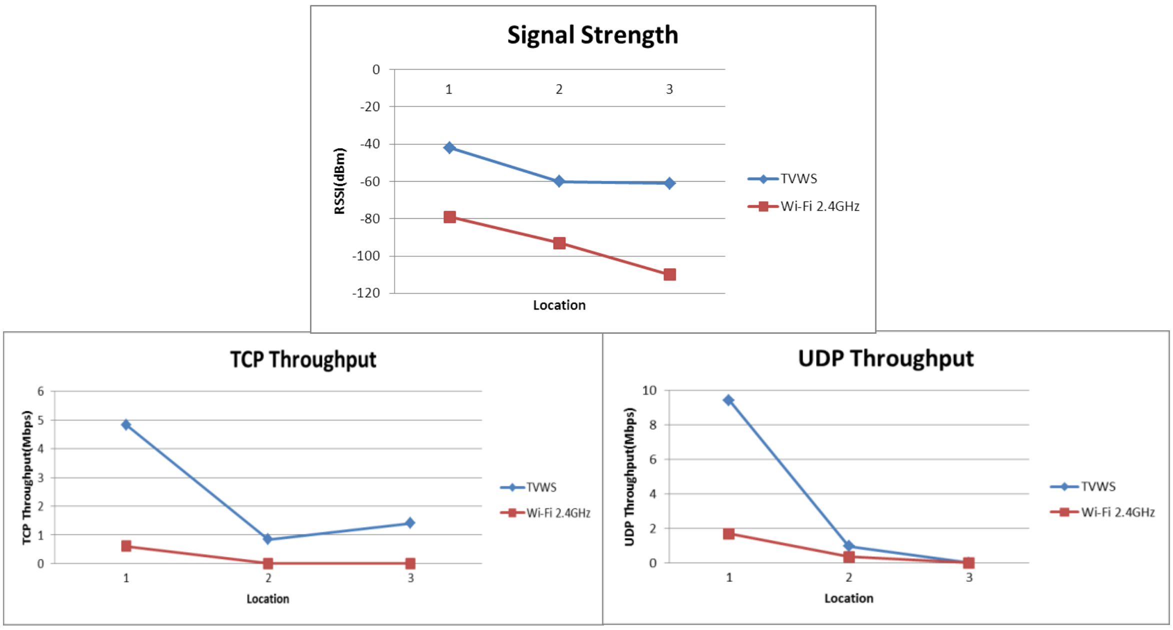

Figure 4-9: Graphed performance measurements for Home 3.

4.1.4 Home 4

Home 4 (shown in Figure 4-10) is a modern, two-storey home constructed 10-15 years ago, with outer walls made from brick and internal walls made from timber and plasterboard. The floor plan and test point locations are shown in Figure 4-11. The base stations (access points) were placed in the lounge, near the window where the BT socket was located. (The BT cable can be seen entering the house just below the lounge window – see yellow circled area in Figure 4-10.) Performance measurements were made with client devices at Locations 1, 2, 3, and 4. (Location 3 is in the garden at the back of the premises.)

Figure 4-10: Home 4 as viewed from the street at the front of the house.

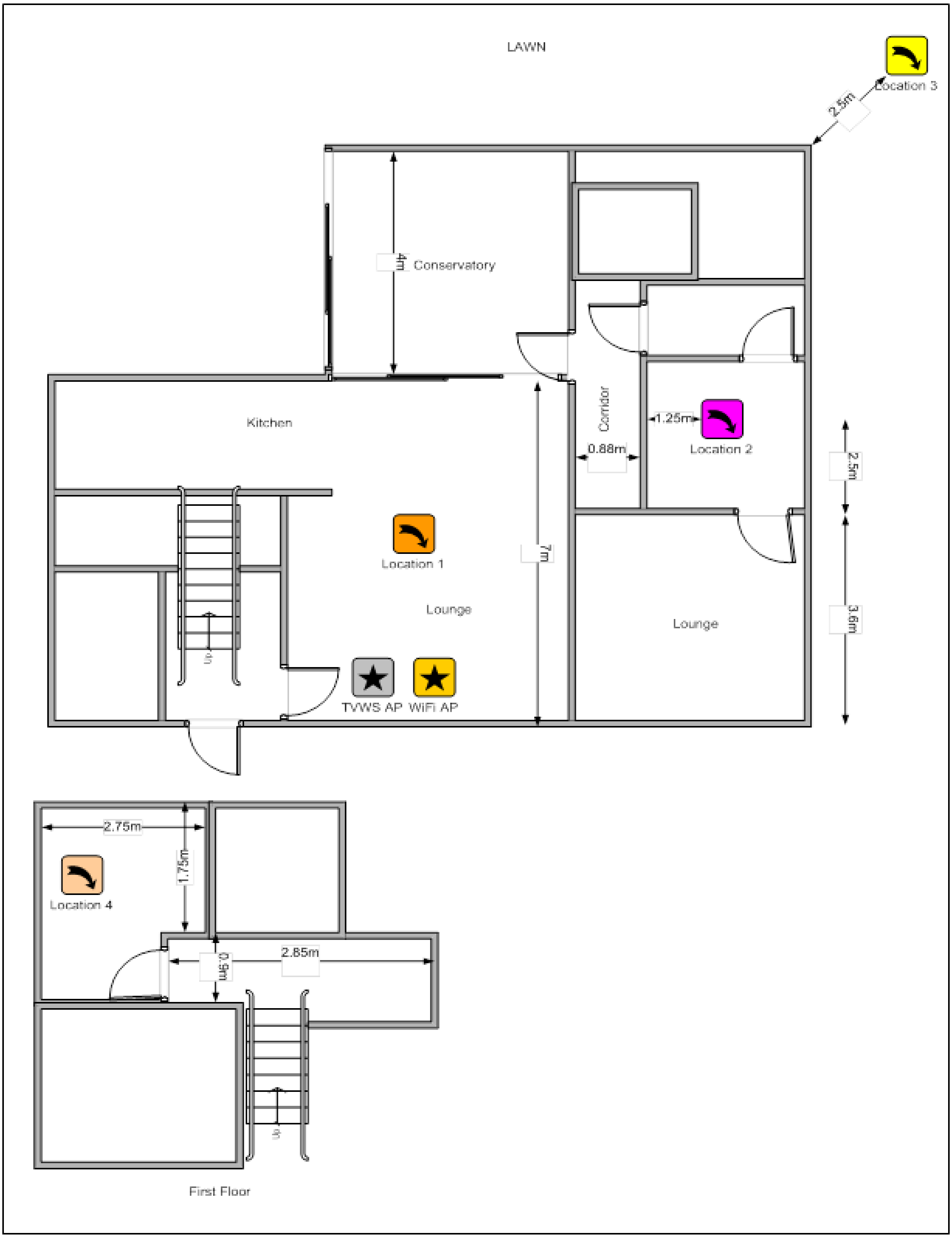

Figure 4-11: Floor plan for Home 4.

The performance results measured in Home 4 are shown in Table 4-4 and are shown graphically in Figure 4-12.

		Home 4						
		Tx Power (dBm)	Chan B/W (MHz)	Received Power (dBm)		Throughput (iperf)		Comment (if applicable)
				Spectrum Analyser	RSSI	TCP (Mbit/s)	UDP (Mbit/s)	
Loc'n 1	802.11af	18	8	-40	-30	10	15	Good Sky video quality
	802.11n (2.4 GHz)	18	20	–	-56	30	40	Good Sky video quality
	802.11n (5 GHz)	18	20	–	-54	30	40	Good Sky video quality
Loc'n 2	802.11af	18	8	-58	-53	11	14	
	802.11n (2.4 GHz)	18	20	-88	-75	28	?	There was an unexplained issue with the functionality of the UDP link during this measurement.
	802.11n (5 GHz)	18	20	-85	-85	4.8	?	There was an unexplained issue with the functionality of the UDP link during this measurement.
Loc'n 3	802.11af	18	8	-69	-64	6.6	11.2	
	802.11n (2.4 GHz)	18	20	Noise Floor	-93	–	–	Unable to establish connection
	802.11n (5 GHz)	18	20	Noise Floor	Noise Floor	–	–	Unable to establish connection
Loc'n 4	802.11af	18	8	-56	-63	7.33	11.3	
	802.11n (2.4 GHz)	18	20	-86	-81	14	?	There was an unexplained issue with the functionality of the UDP link during this measurement.
	802.11n (5 GHz)	18	20	Noise Floor	-57	3.5	?	There was an unexplained issue with the functionality of the UDP link during this measurement.

Table 4-4: Performance results measured in Home 4.

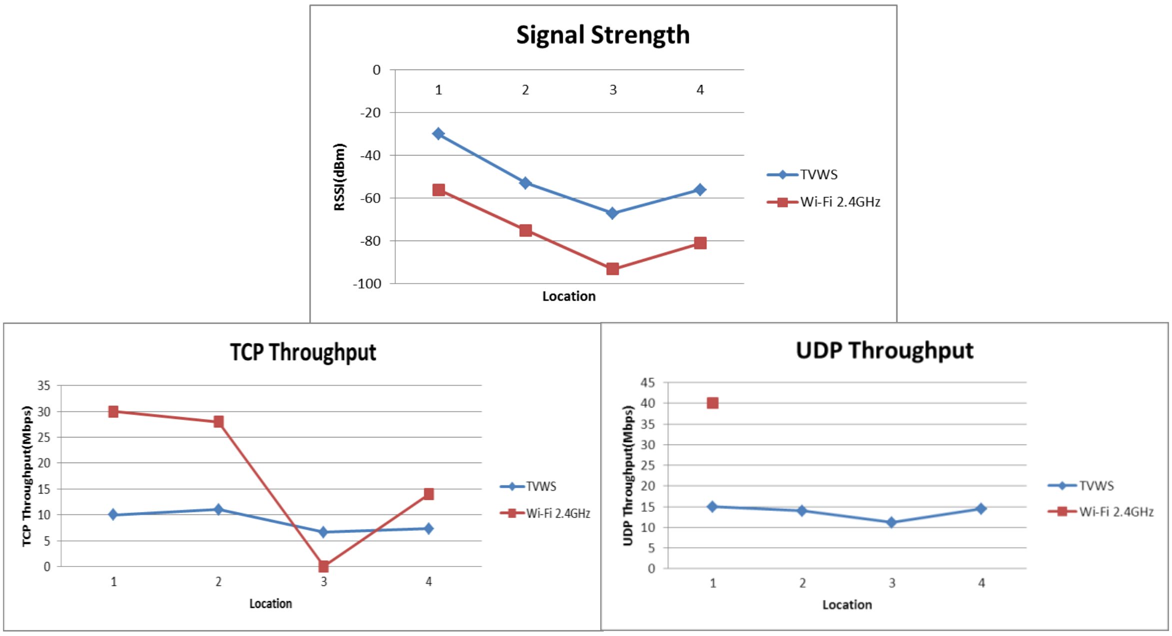

Figure 4-12: Graphed performance measurements for Home 4.

4.2 Signal Strength Measurements in the TV Band

A spectrum analyser was used to examine the spectrum in the TV band (470-790 MHz) at three of the homes used in the trial. According to the Digital UK web site[1], the preferred DTT transmitter for all of the homes is Black Hill, which lies approximately 25 km east of Glasgow's city centre. Eight DTT multiplexes are transmitted from Black Hill, occupying Channels 32, 40, 41, 43, 44, 46, 47, and 51, and Table 4-5 shows the received signal strengths for each of these channels in Homes 1, 2, and 4. (Time constraints prevented DTT signal strength measurements from being made in Home 3.)

Home 1								
Channel	32	40	41	43	44	46	47	51
Centre freq (MHz)	562	626	634	650	658	674	682	714
Multiplex	COM7 HD	BBC B HD	SDN	D3 & D4	ARQ A	BBC A	ARQ B	L-GLW
Tx Power (kW)	43	100	100	100	100	100	100	5
Rec'd signal strength (dBm)	-92	-100	-98	-98	-99	-100	-99	-103
Home 2								
Channel	32	40	41	43	44	46	47	51
Centre freq (MHz)	562	626	634	650	658	674	682	714
Multiplex	COM7 HD	BBC B HD	SDN	D3 & D4	ARQ A	BBC A	ARQ B	L-GLW
Tx Power (kW)	43	100	100	100	100	100	100	5
Rec'd signal strength (dBm)	-105	-	-105	-	-	-	-	-93
Home 4								
Channel	32	40	41	43	44	46	47	51
Centre freq (MHz)	562	626	634	650	658	674	682	714
Multiplex	COM7 HD	BBC B HD	SDN	D3 & D4	ARQ A	BBC A	ARQ B	L-GLW
Tx Power (kW)	43	100	100	100	100	100	100	5
Rec'd signal strength (dBm) in computer room (upstairs)	-87	-90	-95	-96	-95	-95	-100	-105
Rec'd signal strength (dBm) in lounge (downstairs)	-97	-106	-102	-98	-100	-105	-105	-

Table 4-5: DTT received signal strengths for Black Hill transmissions, measured in Homes 1, 2, and 4. (Cells marked '-' signify signal strengths of less than -110 dBm.)

[1] http://www.digitaluk.co.uk/

As can be seen from Table 4-5, the received DTT signal strengths are fairly weak, which is partly due to the fact that the Black Hill transmitter is about 25 km to the east of Glasgow's city centre.[1] The weakness of the signals is also due, however, to the fact that the measurements were made in rooms within each dwelling, rather than on the roofs of the properties. In Home 4, measurements were made at two locations: in upstairs bedroom at the front of the property and in the downstairs lounge, also at the front of the property. The signal strengths measured at those two locations can be clearly seen in Table 4-5 to differ by up to 10 dB.

The south part of Glasgow is served by the Darvel transmitting station, which transmits on Channels 22, 23, 25, 26, 28, 29, and 31, but none of the homes were located within the Darvel coverage area and, as expected therefore, no signals were detected in those channels.

4.2.1 Non-DTT signals

The only DTT signals detected within Homes 1, 2, and 4 were those of Black Hill. However, numerous narrowband signals were also detected in various channels throughout the entire band, with signal strengths typically lying between -90 dBm and -100 dBm. (Those signals had a bandwidth of approximately 200 kHz and were assumed, therefore, to be emanating from wireless microphones.)

Home 1, in particular, had an abundance of such signals in Channel 38, each with a signal strength of about -80 dBm. At the time of the tests, preparations were underway for Commonwealth Games lawn bowling events which were set to take place about 50-100m from the property during the Commonwealth Games period. Roads were closed and various marquees and temporary media centres were being set up, and it was presumed, therefore that the signals in Channel 38 were being generated as a result of these activities.

Similar signals were observed at Homes 2 and 4 across the entire spectrum, and it is assumed that these were also probably related to Commonwealth Games activities.

[1] "TV White Spaces: Approach to Coexistence", Ofcom, September 2013.

5 ANALYSIS AND OBSERVATIONS

The tests that were carried out in each of the four test homes fall essentially into two categories: 1) A comparison of IEEE 802.11af and IEEE 802.11n; and 2) Measurement of spectral usage in the TV band at each home.

5.1 Comparison of IEEE 802.11af and IEEE 802.11n

From the coverage and throughput tests presented in Section 4.1, the following observations may be made:

- For a given transmit power, the coverage achieved by IEEE 802.11af was greater than that achieved by IEEE 802.11n. This was particularly noticeable when signals had to propagate through thick walls: for example, 802.11af was typically able to provide coverage throughout all or most of the homes and was also able to penetrate outer walls and maintain connectivity in nearby garden areas, whereas 802.11n at 5 GHz struggled to penetrate beyond the room in which it was transmitting, and essentially required a line-of-sight in order for a link to be reliably sustained. Typically, the received signal strengths for IEEE 802.11af were some 20-40 dB greater than those for IEEE 802.11n.
- When the IEEE 802.11n device was able to sustain a data link, the data throughput was typically 2-3 times that of the IEEE 802.11af. This may reasonably be expected, since the IEEE 802.11n channel bandwidth of 20 MHz was 2.5 times that of the IEEE 802.11af channel bandwidth of 8 MHz, and the IEEE 802.11n antennas had a gain that was some 4-6 dB greater than that of the IEEE 802.11af antenna.
- For reliable streaming of HD 1080p video, the IEEE 802.11af radios needed a channel that was capable of supporting at least 15 Mbit/s in UDP mode. This proved difficult to obtain in a single TV channel of width 8 MHz; it was achievable when Line-Of-Sight (LOS) conditions existed, but not when Non-Line-Of-Sight (NLOS) conditions existed. It should be noted, however, that MediaTek has a new version of firmware which will be able to support this in NLOS conditions. It is also worth noting that the ability to combine multiple TV channels (so-called channel bonding) is expected to be included in future versions of the IEEE 802.11af radios, and this will allow greater overall data throughput rates to be achieved.

5.2 Spectrum Usage in the TV Band

Spectrum measurements made in three of the test homes revealed that DTT signals received from the Black Hill transmitter were relatively weak, which is partly due to the fact that Black Hill is some 25 km east of Glasgow, and also that the measurements were made indoors rather than on the roofs. No other DTT transmissions were visible from the three homes in which measurements were made.

Narrowband signals, presumably from wireless microphones, appeared to be fairly widespread throughout the band. It is not clear which of those were licensed transmissions and which, if any, were transmissions in breach of regulations. Ofcom is, of course, ultimately responsible for enforcement in respect of unauthorized transmissions, but it is worth noting that this scale of narrowband signals has not been observed during similar trials elsewhere, and it is possible, therefore, that preparations for media coverage of the 2014 Commonwealth Games may have been a contributory factor. (The tests were carried out two weeks before the official start of the Games, and preparations for media coverage were underway in numerous locations across Glasgow.)

6 CONCLUSIONS AND RECOMMENDATIONS

The test results indicate that the IEEE 802.11af radios have the potential to increase the range of broadband coverage over that of IEEE 802.11n systems. Quantifying the amount by which coverage might be improved is difficult, but it was particularly noticeable from the tests described in this report that IEEE 802.11af was able to provide coverage throughout the older homes of sandstone & brick construction while IEEE 802.11n operating at 5 GHz struggled to penetrate beyond the room in which it was transmitting. For the modern home with timber & plasterboard internal walls, the IEEE 802.11n signals were able to provide coverage throughout the home, but coverage in the garden was not achieved. The IEEE 802.11af radios, on the other hand, were able to sustain connectivity throughout the home and into the garden. It is possible that MIMO operation may lead to improved performance for all three types of radio, but the tests were carried out using SISO operation only.

The 1080p HD video content provided by Sky for the tests required a radio link capable of supporting about 15 Mbit/s (UDP), and this proved difficult to achieve using the medium performance driver that was used for the IEEE 802.11af tests. MediaTek expects to incorporate a higher performance driver into its production IEEE 802.11af radios, and it is expected that this will be capable of achieving data throughput rates of 25 Mbit/s (UDP) and 20 Mbit/s (TCP). This will lead to greater ability to support 1080p HD video streaming, although the exact performance will need to be determined from fresh measurements once the new driver has been incorporated.

The IEEE 802.11n radios were configured to operate with a bandwidth of 20 MHz in both the 2.4 GHz band and the 5 GHz band, while the IEEE 802.11af radios had to operate within a single 8 MHz DTT channel. It is expected that future IEEE 802.11af radios will have the ability to combine DTT channels in order to make use of more spectrum; for example, by combining four channels, a total bandwidth of 32 MHz would be available. This requires, of course, that sufficient white space spectrum is available in a particular geographical location, and Ofcom has responsibility for determining this. However, from the spectral measurements that were made at Homes 1, 2, and 4, there appears to be adequate availability of white space spectrum to allow IEEE 802.11af devices to provide useful connectivity, bonding channels when it is advantageous to do so.

6.1 Recommendations and Future Work

The tests described in this report have provided valuable insight into the performance of IEEE 802.11af technology in real-world home environments. The results have shown that IEEE 802.11af has good in-home coverage characteristics, but because the tests were carried out with IEEE 802.11af radio equipment that was still under development, the data throughput achievable was limited and 1080p video streaming proved difficult to achieve using a single 8 MHz TV channel. It would be prudent, therefore, to repeat the tests once the MediaTek radios have been developed to the point where they have the stable, high-performance driver incorporated into them.

The radios also currently operate without using a qualified geo-location database, and it would be informative to repeat the tests once the radios have the ability to use an Ofcom-qualified geo-location database. This would provide valuable information about the performance that is achievable when operating under the Ofcom white space framework, which is ultimately what all white space devices will need to do once the full regulations have been put in place.

It is worth noting that the tests described in this report did not include any attempts to assess whether IEEE 802.11af transmissions cause interference to normal DTT reception. This was briefly considered for inclusion into the test plan, but time constraints ruled it out. It would be useful to carry out such testing, however, as it would help to clarify the extent to which IEEE 802.11af transmissions can successfully co-exist with DTT reception, and this could potentially help to inform Ofcom in its determination of permissible white space transmission powers. Carrying out such tests would, however, require some planning and careful selection of test homes. In particular, it would be necessary to select test homes which are known to have properly-configured DTT installations – some of the test homes used for the current project had no DTT installation.

As a general guideline, an attempt was made to limit the time spent in each home to a maximum of two hours, as it was felt that the home-owner's patience would probably begin to run out beyond that time! It was found in practice, however, that the tests took longer than expected, even though a test plan had been created for use in each home, and this placed limitations on the testing that was ultimately possible. Equipment set-up and configuration was the main time consumer, and it is possible that this could potentially be reduced in the future, once the MediaTek IEEE 802.11af radios become more mature. However, even the IEEE 802.11n radios required set-up and configuration time in each test home, and it would have been advantageous to have used two separate IEEE 802.11n radio set-ups: one pre-configured for testing at 2.4 GHz, the other pre-configured for testing at 5 GHz.

6.2 Concluding Remarks

IEEE 802.11af has significant potential to complement IEEE 802.11n, adding increased in-home coverage capabilities which will complement the capabilities of IEEE 802.11n. MediaTek's tri-band IC product will support all three technologies: IEEE 802.11af in TVWS as well as IEEE 802.11n at 2.4 GHz and 5 GHz. It is expected that samples will be available in Q4, 2015, and this will lead to a range of complementary features and capabilities which Wi-Fi devices may exploit for optimal performance in different situations and circumstances.

7 ACKNOWLEDGEMENTS

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Appendices

A PERFORMANCE FIGURES FOR HIGHER PERFORMANCE IEEE 802.11AF FIRMWARE

Performance figures for the higher performance firmware are shown in Table A-1 and Table A-2 for UDP and TCP, respectively, as measured in the laboratory.

AP mode/Fixed MCS	Throughput(Mbit/s)	PHY Rate (Mbit/s)	MAC Efficiency
802.11af/MCS_0	1.93	2.4	80.42
802.11af/MCS_1	4	4.8	83.33
802.11af/MCS_2	6.12	7.2	85
802.11af/MCS_3	8.23	9.6	85.74
802.11af/MCS_4	12.4	14.4	86.11
802.11af/MCS_5	16.5	19.2	85.95
802.11af/MCS_6	18.3	21.6	84.72
802.11af/MCS_7	20.1	24	83.75
802.11af/MCS_8	23.2	28.2	82.27
802.11af/MCS_9	25.6	32	80

Table A-1: UDP throughput for higher performance firmware.

AP mode/Fixed MCS	Throughput(Mbit/s)	PHY Rate (Mbit/s)	MAC Efficiency
802.11af/MCS_0	1.65	2.4	68.75
802.11af/MCS_1	3.67	4.8	76.46
802.11af/MCS_2	5.34	7.2	74.18
802.11af/MCS_3	7.09	9.6	73.858
802.11af/MCS_4	10.2	14.4	70.838
802.11af/MCS_5	13.7	19.2	71.358
802.11af/MCS_6	14.3	21.6	66.208
802.11af/MCS_7	15.8	24	65.838
802.11af/MCS_8	18.9	28.2	67.028
802.11af/MCS_9	20	32	62.5

Table A-2: TCP throughput for higher performance firmware.