BROADBAND INTELLIGENCE SERIES

TV WHITE SPACE:

Ready for prime time?

Assessing practical realities of a shared-spectrum approach for broadband Internet access

Broadband
Center of Excellence
Resources for a Broadband World

January 2014

University of New Hampshire

Table of contents

Broadband
Center of Excellence

UNH BCoE: Advancing the Broadband Era

The University of New Hampshire Broadband Center of Excellence (www.unhbcoe.org) was established in 2013 to contribute to the advancement of broadband communications as an essential tool for achieving global societal and economic improvements. This report reflects UNH BCoE's role in assessing early-stage technologies that show promise for furthering the availability of affordable broadband access.

TV White Space: An introduction

Broadband Internet access has become an essential element of modern life and a critical enabling agent for the global, information-age economy. As a consequence, assuring ubiquitous and affordable access to broadband Internet service is critical.

Among the more promising solutions for extending broadband's reach into unserved and/or under-served areas is an emerging networking approach known as TV White Space (TVWS), which uses unlicensed, VHF/UHF TV channels to enable the transmission of Internet traffic wirelessly over long distances.

Although it remains in early stages of deployment, TVWS is gaining attention as a possible means to help address critical issues associated with ubiquitous availability and adoption of broadband, as identified by the University of New Hampshire Broadband Center of Excellence (UNH BCoE)[i]:

- **Availability —** What percentage of people, residences and businesses have access to a broadband service in a given area?
- **Adoption —** What percentage of these potential users are actually connected to an available broadband service?
- **Affordability —** In a given area of coverage, how comfortably can an individual or family with average income pay for available broadband services?
- **Performance —** What is the bandwidth of the broadband service to and from the end user?

- **Utilization —** Of the available bandwidth what percentage actually is utilized?
- **Ease of use —** How easy and/or intuitive is it to make use of broadband connectivity and applications?
- **Services —** What applications are available that may compel usage and drive improved network performance?

TVWS exhibits potential not only for extending the availability of broadband access to areas where it is absent, but — at least in certain instances — for serving as an alternative to existing broadband networks where affordability may be an impediment.

Motivations for advancing TVWS as a means for broadband Internet access revolve around both strategic and practical considerations. From a strategy standpoint, there is concern among some Internet sector participants that prevailing broadband delivery networks are narrowly controlled by a few large providers in a way that may limit competition, concentrate power and influence over the Internet and create entry barriers that could hinder service innovation. From a practical standpoint, spectrum sharing in the TVWS frequencies may be useful for extending the availability of high-speed Internet service to communities where traditional broadband Internet services are not available or are prohibitively expensive. As the writer and economist Richard Thanki has commented[ii]:

> **"TV white space spectrum has the potential to be the world's first globally available, broadband-capable licence-exempt band in the optimal sub-1GHz spectrum. In unconnected urban and rural areas, entrepreneurs could use inexpensive, but reliable, Wi-Fi and other types of radio equipment capable of operating on TV band white spaces spectrum to deliver cost-effective broadband services."**

"TV white space spectrum has the potential to be the world's first globally available, broadband-capable licence-exempt band in the optimal sub-1GHz spectrum. In unconnected urban and rural areas, entrepreneurs could use inexpensive, but reliable, Wi-Fi and other types of radio equipment capable of operating on TV band white spaces spectrum to deliver cost-effective broadband services."

— Richard Thanki, economic advisor

Illustrating this point, one of the early TVWS implementations in the U.S. provides high-speed Internet service to a collection of roughly 200 homes in a rural community near Little Rock, Ark. Elizabeth Bowles, the president of the Arkansas Internet service provider Aristotle Inc., told an FCC hearing in November 2013 that TVWS was the only economically feasible medium for serving the relatively low-density area. She calculated that infrastructure costs for delivering service via TVWS frequencies are roughly one-third of costs for more traditional wired or wireless networks. As a result, "It suddenly makes places more feasible — places that right now, because of population density, you can't make an economic case for." At the same FCC hearing, Microsoft Technology Policy Group director Paul Garnett commented that in Kenya, where Microsoft participates in a trial using TVWS to supply solar-powered Internet connectivity, early results have been encouraging in terms of network throughput, range and latency performance. "You can deploy networks using white space today, enabling consumers to gain access who have never had it before," Garnett said.

TVWS also shows promise for emerging as a lower-cost, high-performance solution for delivering broadband access within certain geographies or user sets even in areas where alternative broadband networks operate. For example, students and faculty of West Virginia University are able to connect to the Internet while commuting within the WVE Public Rapid Transit System that serves 15,000 passengers through a TVWS implementation provided through collaboration with the Advanced Internet Regions (AIR.U) higher education networking consortium.

TVWS implementations also are well-suited to support the "Internet of things" — the exploding field of machine-to-machine communications — by providing connectivity over long distances. This is an attribute that is especially welcome in environmental sensing applications where devices must convey data over geographies whose boundaries are beyond the reach of higher-frequency Wi-Fi networks.

This report provides perspectives about the potential for TVWS solutions to emerge as meaningful additions to the broadband Internet delivery marketplace by:

- Explaining the origins and technology underpinnings of TVWS
- Summarizing selected global TVWS trials
- Presenting a financial model for commercial TVWS deployment by Internet Service Providers (ISPs), entrepreneurs and municipalities
- Detailing results of a TVWS field trial conducted in 2013 by the UNH BCoE
- Offering recommendations for advancement of the TVWS category as an economically viable contributor to the broadband Internet ecosystem

Origins and Technology Foundation

TV White Space refers to low-power, unlicensed operation of communications services in unused portions of RF spectrum that fall within frequencies allocated by regulators to television broadcasters in the U.S. and elsewhere. Located in prized spectrum swaths that are notable for their propagation qualities, these channels fall between assigned over-the-air TV frequencies. Although the number of these unused channels varies as a function of location, there is white space spectrum available in almost every U.S. television market, and across much of the developed world, large amounts of white space spectrum remain unused by licensees.

In the U.S., the licensed broadcast TV spectrum was allocated in large swaths roughly between 50 and 800 megahertz (the European range is 470 to 790 MHz). Some of this available spectrum is used for other licensed services, such as wireless microphones used in the entertainment industry. But regardless of license allocations, portions of the spectrum are unoccupied.

TVWS spectrum is valuable in part because it broadcasts signals over long distances. TVWS permits more expansive reach than conventional Wi-Fi networks, which utilize higher frequencies that limit their range. In common commercial “hotspot” deployments — as many a coffee shop visitor has come to realize — Wi-Fi signals have a confined footprint. A typical outdoor Wi-Fi signal travels about 100 meters, versus TVWS signals that may extend to 400 meters at the same power level, or up to as far as 10 km at higher power. This impressive reach has spawned the nickname “Super Wi-Fi” for TVWS networks.

In addition to their impressive range, VHF and UHF frequencies are able to convey energy through physical obstacles. Just as TV signals have done for more than 70 years, radio signals traversing these frequencies have excellent potential to penetrate buildings and walls. These propagation characteristics allow TVWS-enabled broadband access networks to connect over long distances without line-of-sight restrictions, and/or to enable very fast Internet connectivity over short distances and through physical obstacles.

As a result of these core characteristics — superior range and physical penetration coupled with unlicensed access to spectrum — the economics of TVWS networks become attractive. In testimony delivered to the FCC in January 2013, Google and Microsoft pointed out that these advantages could be important in encouraging new entrants to deliver broadband access to underserved areas. “Additional unlicensed spectrum, particularly in the TV band, with its superior propagation characteristics for wide-range, non-line of sight operations, will facilitate further broadband expansion by [Wireless Internet Service Providers] into areas least likely to be served by traditional ISPs. Lower frequency spectrum will allow deployment of fewer antennas operating at lower power levels,” the companies said.

An important component of this economic appeal has to do with the “unlicensed” operation of TVWS spectrum. Because there is no direct cost required to use or acquire unlicensed white space spectrum, the cost associated with TVWS as an Internet transmission medium is instead mainly tied to developing technologies such as antennae and radios that make use of TVWS. As other unlicensed frequencies such as Wi-Fi have demonstrated, the absence of formidable spectrum costs can produce a rich pool of products and innovations powered by economies of scale. A prolific range of inexpensive Wi-Fi devices and Bluetooth-compatible accessories — both categories are associated with unlicensed frequencies — underscores how the availability of unlicensed spectrum can spur investment and create scale economies that benefit consumers.

For these reasons and others, various proponents view TVWS as a promising, low-cost and affordable addition to the U.S. and global broadband Internet delivery infrastructures.

- The FCC, in its 2010 Order expressing rules for the use of TVWS frequencies, observed that “This block of spectrum is ripe for innovation and experimental use, holding rich potential for expanding broadband capacity and improving access for many users…”[iii]
- The Internet services company Google, which maintains a database of white space frequencies for U.S. TVWS initiatives, believes TVWS “could help bridge the digital divide by providing wireless Internet to rural areas and help enable technology innovation.”[iv]
- Microsoft, which has engaged in several prominent TVWS trials and projects, observes that “This under-utilized spectrum is proving to be a key part of the future of not just universal broadband access but of the solution for the explosion of devices connecting the Internet.”[v]
- Economist Richard Thanki, who analyzes broadband communications issues, writes that “TV white spaces could be used to connect many of the billions of people currently without affordable access to the Internet, enable a global market in machine-to-machine communications, and increase the resilience of networks in the face of natural and manmade disasters.”[vi]
- Microprocessor maker Intel also has high hopes for TVWS technology. “TV white space will be an absolutely key enabling technology for intelligent living. It is essentially free to use, it is underutilized and you get great broadband performance from it,” Martin Curley, vice-president of Intel's European research labs, told the publication *New Scientist* in October 2013.[vii]

Regulatory principles

The fact that TVWS is available at all as a medium for broadband Internet access reflects a changing approach to the allocation of spectrum, a prized resource that belongs to the public. As governments recognize the critical value of communications in the Internet era, there is a corresponding desire to find ways to maximize the value of the physically limited electromagnetic spectrum. TVWS is a prominent example of how unused frequencies may be put to use without a license requirement while protecting incumbent/licensed users in their specified areas.

Emerging and established regulatory approaches for freeing up the use of TVWS bands depend on the concept of dynamic spectrum access, which enables wireless devices to identify and make use of spectrum that is unused at a particular location and/or at a particular time. Achieving managed access to this shared spectrum is accomplished by reference to a geolocation database that stores and expresses upon query permissible frequencies and operating parameters. In the U.S., for example, TVWS devices abide by a fluid schedule that provides the list of available channels in a 48-hour time period and dictates rules around power output and other constraints that guard against interference with licensed users such as TV stations. Four providers have been authorized by the FCC to provide publicly accessible TVWS databases in the U.S. as of November 2013:

- Google
- iconectiv
- Key Bridge Global
- Spectrum Bridge

An example of a query result from Key Bridge Global's TVWS database below indicates frequencies that may be used in the Oklahoma City area at specified antenna heights. The table below shows, for example, that channel 2 may be accessed by unlicensed white space devices from fixed access antenna points located at Height above Average Terrain (or HAAT) levels of 30 meters and less.

White Space Calculator Mapped Results White Space Channel Availability Results Summary for 35.460682, -97.502320 (WGS_84)

CH	FIXED									MODE II		LPAUX
	<3	3-10	10-30	30-50	50-75	75-100	100-150	150-200	200-250	100	40	
2 [54 - 60 MHz]	✓	✓	✓	■	■	■	■	■	■	⊘	⊘	✓
3 [60 - 66 MHz]	⊘	⊘	⊘	■	■	■	■	■	■	⊘	⊘	⊘
4 [66 - 72 MHz]	⊘	⊘	⊘	■	■	■	■	■	■	⊘	⊘	⊘
5 [76 - 82 MHz]	✓	✓	✓	■	■	■	■	■	■	⊘	⊘	✓
6 [82 - 88 MHz]	✓	✓	✓	■	■	■	■	■	■	⊘	⊘	✓
7 [174 - 180 MHz]	×	×	×	■	■	■	■	■	■	⊘	⊘	×
8 [180 - 186 MHz]	×	×	×	■	■	■	■	■	■	⊘	⊘	✓
9 [186 - 192 MHz]	✓	✓	✓	■	■	■	■	■	■	⊘	⊘	✓
10 [192 - 198 MHz]	✓	✓	✓	■	■	■	■	■	■	⊘	⊘	✓
11 [198 - 204 MHz]	✓	✓	✓	■	■	■	■	■	■	⊘	⊘	✓
12 [204 - 210 MHz]	×	×	×	■	■	■	■	■	■	⊘	⊘	✓
13 [210 - 216 MHz]	×	×	×	■	■	■	■	■	■	⊘	⊘	×
14 [470 - 476 MHz]	×	×	×	■	■	■	■	■	■	⊘	⊘	✓
15 [476 - 482 MHz]	×	×	×	■	■	■	■	■	■	⊘	⊘	×

Source: Key Bridge Global White Space Channel Calculator. Accessed Dec. 5, 2013

Lookup tables like the one pictured above are a critical ingredient in a more permissive attitude toward TVWS frequency usage that regulators including the FCC and the U.K.'s Ofcom have adopted or are contemplating. In seeking to allow productive use of the unoccupied spectrum, the FCC in 2010 decided to allow the unused TVWS to be made available for unlicensed broadband wireless devices. In the FCC's words[viii]:

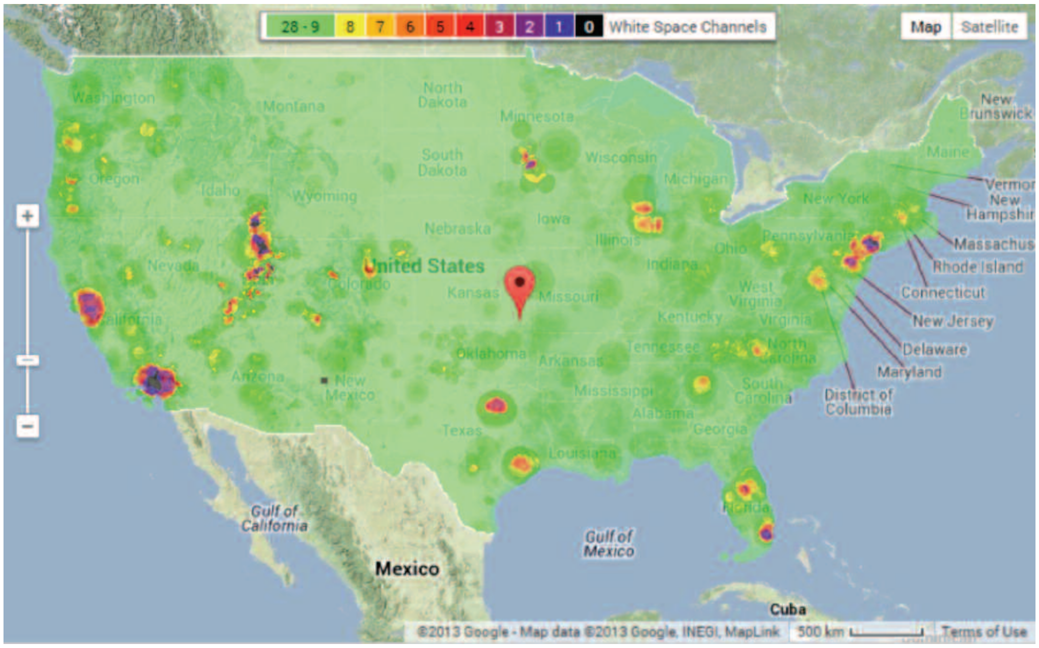
> **"Access to this spectrum could enable more powerful public Internet connections — super Wi-Fi hot spots — with extended range, fewer dead spots, and improved individual speeds as a result of reduced congestion on existing networks. Many other applications are possible, such as broadband access to schools particularly in rural areas, campus networks that are better able to keep pace with user's increasing demands for bandwidth, home networks that are better able to support real time streaming video applications, remote sensing of water supplies by municipalities and support for the smart grid."**

"Access to this spectrum could enable more powerful public Internet connections — super Wi-Fi hot spots — with extended range, fewer dead spots, and improved individual speeds as a result of reduced congestion on existing networks. Many other applications are possible, such as broadband access to schools particularly in rural areas, campus networks that are better able to keep pace with user's increasing demands for bandwidth, home networks that are better able to support real time streaming video applications, remote sensing of water supplies by municipalities and support for the smart grid."

— Federal Communications Commission

Amended rules adopted by the FCC in 2012 relaxed earlier interference protection rules and raised HAAT limits, cheering TVWS category participants. The more permissive rules are seen as reducing technology costs, freeing up more potential channels, extending propagation ranges and potentially improving the economics of TVWS deployment in more populated areas. (The U.S. National Association of Broadcasters in 2012 dropped a lawsuit challenging the FCC's decision to free up unused spectrum.)

The spectrum map below indicates that in most areas of the U.S., nine or more TVWS channels were available as of December 2013.



Source: Google TV White Space Spectrum Database, December 2013

The amount of available TVWS spectrum depends on the device physical location, the height of the device antennas and whether fixed or portable operation is planned. In the U.S., the FCC permits two categories of unlicensed devices: fixed and personal/portable. A "fixed" white space operation relies on a stationary device that might be used to provision a Wi-Fi hotspot, for example, and transmits at less than 4 Watts Effective Instantaneous Radiated Power (EIRP). A "portable/personal" white space implementation propagates a signal over a smaller footprint from a device such as a laptop computer or smartphone because its maximum power must be less than 0.04 Watts EIRP.

Spectrum availability can vary substantially even between nearby areas. An example: For 10-meter high antennas in Durham, N.H., where the UNH BCoE is based, the number of unused TV channels is 14, equating to 84 MHz of available spectrum. By way of contrast, for the same antenna height the upper valley area surrounding Hanover, N.H., has 18 unused channels equivalent to 108 MHz of available spectrum.

Despite the variations, these amounts of available spectrum are significant when equipment can be reasonably expected to provide in the range of 5 to 20 megabits per second of throughput within a single unused 6 MHz TV channel depending on the local terrain and distance between two devices.

The fact that TVWS depends on regulatory permissiveness elevates the stakes associated with forthcoming spectrum usage and allocation policies under consideration in the U.S. and elsewhere. Deeper investment in TVWS technologies hinges in part on establishment of certainty around long-term access to spectrum.

Architecture requirements

A typical architecture for a broadband access system using TVWS frequencies consists of these main components:

- A central base station that is connected to a high-speed backbone Internet connection on one side and a transmitting antenna up to 108 feet from ground on the other side which is aware of its location and the location of devices to which it is connected
- A customer premise equipment (CPE) device which is connected to an antenna at a user's home (or business) location
- A central database service that makes known to the TVWS equipment what TV channels are unused in the locations where the equipment is deployed
- Network management systems to configure and control the TVWS equipment

Using this general architecture, an ISP can provide broadband access services to an area that falls outside the reach of traditional broadband access networks. So long as a network user is located within roughly a five-mile radius of a centrally located antenna with a high-speed connection to the Internet — say a town hall or school or library — an ISP can install a TVWS base station on the building using a mast of sufficient height that addresses distance and reach requirements as well as terrain topology. Signals from the TVWS base station would be broadcast from that location with a range of several miles. The ISP might then use this TVWS broadband access network to connect multiple users to the Internet, effectively allowing them to share the library or school network while enjoying higher data rates and/or improved latency versus dial-up or satellite Internet networks.

Standards and technology

Work has also proceeded to establish early standards for TVWS.

- The IEEE 802.22 data link standard that was ratified in 2011 specifies the air interface and important functions like access control, quality of service and security.
- 802.11af, ratified in December 2013, defines international specifications for spectrum sharing among unlicensed white space devices and licensed services in the TVWS band. 802.11af provides a common architecture, a communication scheme, and a control structure for permitting TVWS devices to share spectrum with incumbent services.
- IEE 802.15TG4m is a newer study group formed to evaluate and develop specifications for lower-speed, longer-range WRAN in wireless bands.

Activity is building on the device front as well. There are several manufacturers of TVWS base stations and customer premise equipment that use differentiated, proprietary technology solutions (see list). Additionally, the FCC has certified four TVWS databases.

Selected TVWS technology developers/vendors

COMPANY	LOCATION	SPECIALIZATION
6Harmonics Inc.	Ottawa, Canada	Smart antenna, cognitive radio systems
Adaptrum	San Jose, Calif.	TVWS radio systems
Carlson Wireless	Arcata, Calif.	TVWS radio systems
Neul	Cambridge, U.K.	Silicon for wide-area wireless networks

Deployments and Findings

TVWS technology has been tested since 2009, yet remains in a relatively early stage of its development. The first U.S. trials were conducted in 2009 in:

- Claudville, Va., where Microsoft Corp. worked with several partners to connect the community's post office, several homes and businesses and a local school to a fiber optic network using prototype TVWS equipment under an experimental FCC license.
- Redmond, Wash., where Microsoft implemented a TVWS network providing Internet access to company vehicles that shuttled employees and visitors across the company's one-mile wide campus.

Since then, a number of trials have been staged in the U.S. and elsewhere to develop more knowledge about the technology's potential.

U.S. deployments:

Wilmington, N.C.: A municipal “smart city” wireless network launched in 2010 provides services including energy and traffic monitoring and connectivity to public Wi-Fi networks via an experimental license.

West Virginia University: In July 2013, West Virginia University began using vacant broadcast TV channels to provide the campus and nearby areas with wireless broadband Internet services. In partnership with the Advanced Internet Regions (AIR.U) consortium, the network was designed initially to provide Internet connectivity to a free public Wi-Fi access network available for students and faculty at public transit platforms. The implementation involves a two-channel TVWS base station from the manufacturer Adaptrum, with receive systems at five transit locations. Downstream data rates are consistently above 12 Mbps.

Yurok Tribe, California: In January 2013, the tribe signed a memorandum of understanding with Carlson Wireless Technologies for the RuralConnect IP project, which uses TVWS frequencies to deliver Internet traffic to rural households located in a difficult-to-access location. RuralConnect IP received an FCC experimental license for the trial.

Arcata, California: Carlson Wireless Technologies and Cal.net formed an alliance and received an FCC-granted Special Temporary Authority to provide a large-scale deployment of commercial TVWS products. The project comprises multiple transmission sites delivering broadband to several hundred previously unserviceable subscribers in El Dorado County.

Thurman, N.Y.: This rural community in New York’s Warren County is implementing a TVWS network to offer high-speed Internet access to households in areas beyond the reach of digital subscriber line and cable broadband access networks. Installation and testing began in late 2013.

Gigabit Libraries Project: Pilot trials in five U.S. states have been initiated in 2013 as part of a program to assess the suitability of TVWS for delivering high-speed Internet access both to on-site library patrons and to nearby areas that are unserved or underserved by traditional broadband network providers. (See detail on UNH BCoE’s Gigabit Libraries Project trial below.)

International deployments:

Mawingu White Space Broadband Project: Microsoft and its partners (Kenyan Internet service provider Indigo Telecom Ltd. and wireless technology provider Adaptrum) are delivering wireless broadband access using TVWS frequencies to school and healthcare facilities near Nanyuki, Kenya, in a pilot deployment that began in February 2013.

Limpopo, Africa: A pilot project launched by Microsoft in July 2013 relies on the University of Limpopo as a hub for a TVWS network that provides wireless connectivity to five secondary schools in remote parts of the Limpopo province.

Tanzania Commission for Science and Technology: A collaboration of local Internet provider UhuruOne, Microsoft and the commission, this TVWS trial announced in May 2013 provides wireless Internet access to students and faculty members at the University of Dar es Salaam.

Singapore White Spaces Pilot Group: The group has undertaken three projects designed to prove the suitability of TVWS technology as a broadband Internet medium in environments where traditional wireless connectivity is challenging. Installations involve the National University of Singapore (climate control metering), the Singapore Island Country Club (smart sensor technology) and Singapore’s Changi shipping port district (Internet connectivity for ship crews). Participants are Microsoft, Institute for Infocomm Research (I2R), StarHub, Neul, Adaptrum, Power Automation, the Singapore Island Country Club, Spectrum Bridge, ZDW Systems, Grid Communications, Terrabit Networks and National Institute of Information and Communications Technology (NICT) Japan.

Ofcom/U.K.: Ofcom, the U.K. communications regulator, is planning a 2014 pilot of innovative white space technology in the U.K., among the first of its kind in Europe. Using white spaces between airwaves reserved for digital terrestrial TV broadcasting (470 MHz to 790 MHz), the pilot aims to test interactions between devices, databases and Ofcom; to provide an opportunity for industry to conduct trials using the proposed framework; and to gain further information on the coexistence issues between new use by white space devices and existing use for digital terrestrial television. The trial will run across citywide and rural locations and involved 20-plus industry and public sector participants as of December 2013.

South Africa: Google has launched a partnership with the Independent Communications Authority of South Africa and Carlson Wireless to deliver wireless access to 10 schools through three base stations at the campus of Stellenbosch University's Faculty of Medicine and Health Sciences in Tygerberg, Cape Town.

Montevideo, Uruguay: Microsoft has secured an experimental license from Uruguay's telecoms regulator to set up a white-space data network.

Cambridge TV White Spaces Trial

Among the most far-reaching to date was a 2011-2012 pilot deployment in Cambridge, U.K., where a consortium of 17 companies participated in a multi-faceted trial of TVWS as a medium for broadband Internet transmission. Selected findings follow.

Date: June 2011 — April 2012

Purpose: Demonstrate how the use of white spaces could enable a range of new applications, including rural broadband and machine-to- machine communications, without disrupting existing services in the UHF bands.

Participants: Cambridge White Spaces Consortium (Adaptrum, Alcatel-Lucent, Arqiva, BBC, BSkyB, BT, Cambridge Consultants, CRFS, CSR, Digital TV Group, Microsoft, Neul, Nokia, Samsung, Spectrum Bridge, TTP and Virgin Media)

Technology providers: 6 Harmonics, Adaptrum, KTS, Neul

Network configuration: 8 base stations (5 within urban/city locations, 3 in rural locations) connected by feeder cable to dual omnidirectional antennas mounted at roof-top level, typically at height of 10 meters. Signal performance was measured from both fixed sites plus a vehicle-mounted antenna at various locations.

Key findings: Within the urban/city deployment, the Cambridge trial resulted in:

- Coverage of up to 1.5 km for fixed reception at 10 m and around 400 m for mobile reception at the coverage edge
- Total useful TCP-IP bandwidth of between 2 Mbps and 13 Mbps (uplink and downlink combined) dependent upon the received RF signal level at the test point
- Significant differences in spectrum quality for the two TVWS channels used

For its rural deployment, the group was able to achieve an Internet service speed of up to ~8 Mbps downlink, while a corresponding ~1.5 Mbps uplink was established to a residence located 5.6 km away from the base transmitter over a single TVWS channel.

Note: Full report findings from the Cambridge trial are available at http://research.microsoft.com/en-us/projects/spectrum/cambridge-tv-white-spaces-trial-recomms.pdf

Financial modeling

The availability of attractive spectrum without licensing costs gives TVWS technology potential to support Internet service deployment to communities and neighborhoods with relatively modest investment levels, potentially creating economic activity and employment opportunities.

Business model scenarios for TVWS network deployments include these possibilities:

1) An existing ISP that operates a TVWS network as an extension of its broadband network within or around an existing area of service
2) A local entrepreneur who undertakes the role of system integrator and ISP provider using TVWS technology and resources
3) A municipality or local government that uses TVWS to extend the reach of broadband service to areas where it is not available
4) A local library, university or other institution that performs as an ISP and system integrator using TVWS technology
5) An existing ISP that uses TVWS to establish a new broadband network in an area where the ISP had not previously operated
6) A municipality or local government that uses TVWS to introduce broadband to a community that has not previously had access to it

UNH BCoE has developed general financial models to assist in assessment and planning for TVWS implementations. The Profit and Loss statements for these TVWS models (one designed for commercial implementation and one for municipal implementation) are based on scenarios involving three differentiated serving areas surrounding base/transmission facilities:

- **An urban area** that is closest to the base station and transmitting antenna and is served by higher-order QAM modulation.
- **A suburban area** farther from the base station served by a modulation scheme that provides a tradeoff between performance and robustness.
- **A rural serving area** served by a modulation scheme producing lower performance but improved robustness.

Assumptions and Notes

1. The model is designed based on a five-year return on investment horizon.
2. The usage model determines the communication infrastructure required as the subscriber penetration grows over the five-year period.
3. The cost model supports budgetary pricing for current generation as well as next-generation equipment; in the examples shown in this report, next-generation pricing is incorporated.
4. The cost model supports a definable subscriber penetration and growth over the five-year period.
5. Reflecting that each TVWS deployment is unique, most parameters are programmable including operating expenses, equipment costs, depreciation schedules, topology configuration, subscriber penetration and growth. This model represents only one deployment scenario.
6. Parameters can be tailored to specific demographic and topological requirements to fit individual circumstances.
7. The usage model uses aggregate monthly consumption data per subscriber derived from Sandvine Global Internet Phenomena snapshot for fixed access in N America for 2H of 2013.
8. Based on area of coverage demographics programmed into the examples below, the system will support 726 subscriber locations at year five growing from 73 in year one. Actual deployments will vary.
9. Nothing herein shall constitute financial advice or be relied on as such.

(Note: Customizable financial models, allowing for variable inputs for market size, demand assumptions and other factors, are available for download in Microsoft Excel® format at https://unhbcoe.org/tv-white-space-planning-worksheets)

TVWS P&L Year 1 through 5 — Commercial

	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5
Customers	**73**	**182**	**363**	**545**	**726**
Subscriber Additions	73	109	182	182	182
Subscriber Revenue					
Revenue — Internet	$39,195	$97,988	$195,976	$293,965	$391,953
Revenue — Equipment Rental	$5,750	$14,375	$28,750	$43,124	$57,499
Total Revenue	**$44,945**	**$112,363**	**$224,726**	**$337,089**	**$449,452**
Other Income					
Total Grants	$—	$—	$—	$—	$—
Total Income	**$44,945**	**$112,363**	**$224,726**	**$337,089**	**$449,452**
Cost of Sales					
Marketing and Promotions	$4,349	$4,349	$4,349	$4,349	$4,349
Infrastructure equipment installation	$450	$225	$675	$675	$450
Client equipment installation	$4,084	$6,126	$10,209	$10,209	$10,209
Total Cost of Sales	**$8,882**	**$10,699**	**$15,233**	**$15,233**	**$15,008**
Gross Profit	**$36,063**	**$101,664**	**$209,493**	**$321,856**	**$434,444**
Debt Service					
New debt — electronics	$46,225	$42,338	$72,563	$72,563	$71,063
New debt — infrastructure & land	$125,000	$—	$—	$—	$—
Interest on total debt	$8,241	$9,464	$11,646	$13,098	$13,716
Depreciation					
Infrastructure — Tower, Building & BU Power	$6,333	$6,333	$6,333	$6,333	$6,333
Electronics — Base Station & Antenna	$600	$900	$1,800	$2,700	$3,300
Electronics — Client Unit & Antenna	$5,445	$13,613	$27,225	$40,838	$54,450
Electronics — Backoffice Systems	$3,200	$3,200	$3,200	$3,200	$3,200
Startup Costs	**$55,000**	**$—**	**$—**	**$—**	**$—**
Operating Expenses					
Internet Connection Costs					
Backbone Access Fee	$10,000	$10,000	$10,000	$10,000	$10,000
Internet Utilization Fee	$1,185	$2,964	$5,927	$8,891	$11,855
Payroll	$8,712	$21,780	$43,560	$65,340	$87,120
Contract Services					
Accounting & Legal	$25,000	$25,625	$26,266	$26,922	$27,595
Billing and Processing	$3,630	$9,075	$18,150	$27,225	$36,300
TVWS Engineering Services	$12,000	$6,000	$2,000	$2,000	$2,000
Office Expenses	$15,000	$15,375	$15,759	$16,153	$16,557
Miscellaneous					
Insurance	$12,000	$12,300	$12,608	$12,923	$13,246
Auto/Truck	$12,000	$12,300	$12,608	$12,923	$13,246
Miscellaneous	$12,000	$12,300	$12,608	$12,923	$13,246
Operating Costs					
Operating cost — client electronics	$2,723	$6,806	$13,613	$20,419	$27,225
Operating cost — infrastructure electronics	$300	$450	$900	$1,350	$1,650
Operating cost — software maintenance	$1,000	$1,000	$1,000	$1,000	$1,000
Operating Expenses per Household per month	**$132.63**	**$62.43**	**$40.17**	**$33.37**	**$29.96**
Total Startup, Expenses, Depreciation & Interest	**$194,369**	**$169,485**	**$225,202**	**$284,237**	**$342,039**
Profit					
Profit before Taxes	**$(158,307)**	**$(67,821)**	**$(15,709)**	**$37,619**	**$92,405**

Source: UNH BCoE, 2014

TVWS P&L Year 1 through 5 — Municipal

	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5
Customers	**73**	**182**	**363**	**545**	**726**
New Customers	73	109	182	182	182
Customer Revenue					
Revenue — Internet	$39,195	$97,988	$195,976	$293,965	$391,953
Revenue — Equipment Rental	$5,750	$14,375	$28,750	$43,124	$57,499
Total Revenue	**$44,945**	**$112,363**	**$224,726**	**$337,089**	**$449,452**
Other Income					
Total Grants	$—	$—	$—	$—	$—
Total Income	**$44,945**	**$112,363**	**$224,726**	**$337,089**	**$449,452**
Cost of Sales					
Marketing and Promotions	$4,349	$4,349	$4,349	$4,349	$4,349
Infrastructure equipment installation	$450	$225	$675	$675	$450
Client equipment installation	$4,084	$6,126	$10,209	$10,209	$10,209
Total Cost of Sales	**$8,882**	**$10,699**	**$15,233**	**$15,233**	**$15,008**
Gross Profit	**$36,063**	**$101,664**	**$209,493**	**$321,856**	**$434,444**
Debt Service					
New debt — electronics	$46,225	$42,338	$72,563	$72,563	$71,063
New debt — infrastructure & land	$15,000	$—	$—	$—	$—
Interest on total debt	$2,856	$4,337	$6,791	$8,529	$9,447
Depreciation					
Infrastructure — Tower, Building & BU Power	$1,000	$1,000	$1,000	$1,000	$1,000
Electronics — Base Station & Antenna	$600	$900	$1,800	$2,700	$3,300
Electronics — Client Unit & Antenna	$5,445	$13,613	$27,225	$40,838	$54,450
Electronics — Backoffice Systems	$3,200	$3,200	$3,200	$3,200	$3,200
Startup Costs	**$25,000**	**$—**	**$—**	**$—**	**$—**
Operating Expenses					
Internet Connection Costs					
Backbone Access Fee	$—	$—	$—	$—	$—
Internet Utilization Fee	$593	$1,482	$2,964	$4,446	$5,927
Payroll	**$8,712**	**$21,780**	**$43,560**	**$65,340**	**$87,120**
Contract Services					
Accounting & Legal	$10,000	$10,250	$10,506	$10,769	$11,038
Billing and Processing	$3,630	$9,075	$18,150	$27,225	$36,300
TVWS Engineering Services	$12,000	$6,000	$2,000	$2,000	$2,000
Office Expenses	**$3,000**	**$3,075**	**$3,152**	**$3,231**	**$3,311**
Miscellaneous					
Insurance	$12,000	$12,300	$12,608	$12,923	$13,246
Auto/Truck	$12,000	$12,300	$12,608	$12,923	$13,246
Miscellaneous	$12,000	$12,300	$12,608	$12,923	$13,246
Operating Costs					
Operating cost — client electronics	$2,723	$6,806	$13,613	$20,419	$27,225
Operating cost — infrastructure electronics	$300	$450	$900	$1,350	$1,650
Operating cost — software maintenance	$1,000	$1,000	$1,000	$1,000	$1,000
Operating Expenses per Household / month	**$89.48**	**$44.45**	**$30.69**	**$26.71**	**$24.71**
Total Startup, Expenses, Depreciation & Interest	**$116,058**	**$119,868**	**$173,683**	**$230,813**	**$286,706**
Profit					
Profit before Taxes	**$(79,995)**	**$(18,204)**	**$35,810**	**$91,043**	**$147,738**

Source: UNH BCoE, 2014

UNH BCoE TVWS Trial: Findings and Detail

Introduction and background

In September 2013, the UNH BCoE was selected as one of five applicants to participate in pilot deployments of TVWS technology as part of the Gigabit Libraries Project, an initiative aimed at providing broadband Internet services to unserved and underserved communities through public library facilities.

The project was designed to assess the performance of TVWS technology as a means to provide high-speed Internet connectivity to area public libraries, and by extension, to evaluate the suitability of TVWS as a solution for extending high-speed Internet availability from libraries to residences and businesses that are not served by traditional broadband IP networks.

As a participant in the Gigabit Libraries TVWS assessment, UNH BCoE provided:

- **Physical infrastructure and resources.** The UNH campus environment provided a foundational infrastructure on which to deploy the TVWS base station.
- **Established test and measurement facilities.** The UNH InterOperability Laboratory (IOL), a nationally recognized technology testing environment, offered highly skilled staff and a well-instrumented client station test site upon which to collect extensive link characteristics.
- **A challenging deployment environment.** The UNH base station and client sites provided a challenging RF environment in which to operate — driving the technology and equipment to (and beyond) its limits and enabling BCoE staff to work with the vendor to identify and address issues and improve future offerings.
- **Technology expertise.** The TVWS project was managed and evaluated by knowledgeable staff with deep experience in similar technology at a similar level of maturity: first generation cable modem technology. This report reflects input and analysis from the BCoE team of experts.

Pilot scope and geography

The pilot project was designed to provision TVWS links from a single base station to three or more locations including community libraries, UNH campus library facilities and the UNH IOL, a testing center for commercial-grade advanced technology. Carlson Wireless of San Jose, Calif., was selected to provide base station and transmission equipment for the trial.

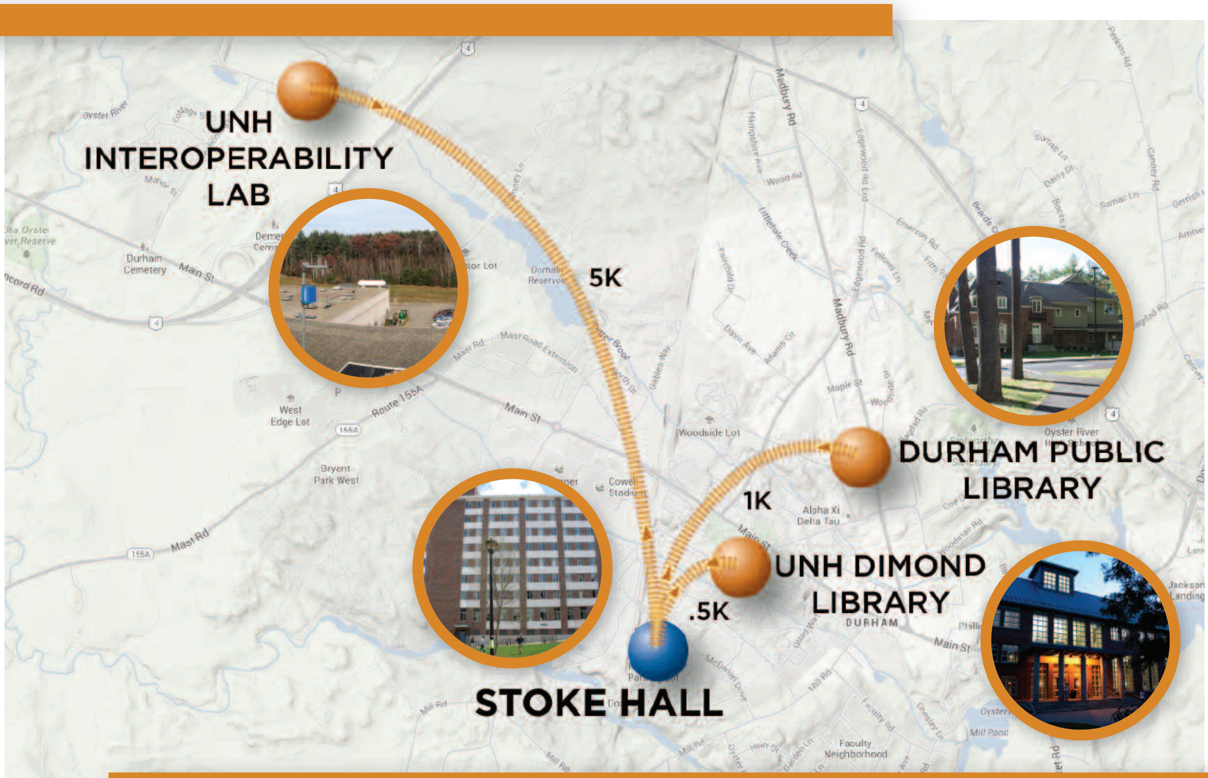
In October 2013, the TVWS base station was installed within a protected/interior closet located on the top floor of a UNH residence hall (Stoke Hall), where it connected to the campus wide-area Internet delivery network. A ¾-inch feeder cable connected the base station to an outdoor omnidirectional antenna mounted at an approximate height of 103 feet from the rooftop of the building (image at left).

The trial used the VHF frequency of 635 MHz (channel 41), which was indicated as an available channel by the Google TVWS database used to determine frequency availability.

Three locations were selected and implemented for the trial:

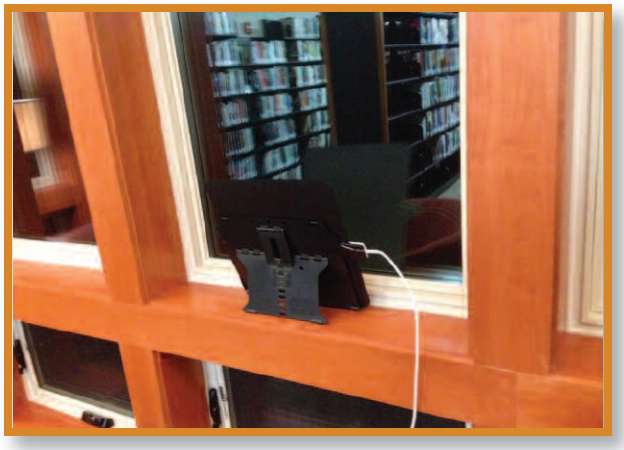
- The Durham, N.H., Public Library, located approximately 1 km from the TVWS base station
- The UNH Dimond Library, located approximately .5 km from the TVWS base station
- The UNH IOL, located approximately 5 km from the TVWS base station

The diagram below depicts the connection points involved in the UNH BCoE trial:



Client side technology

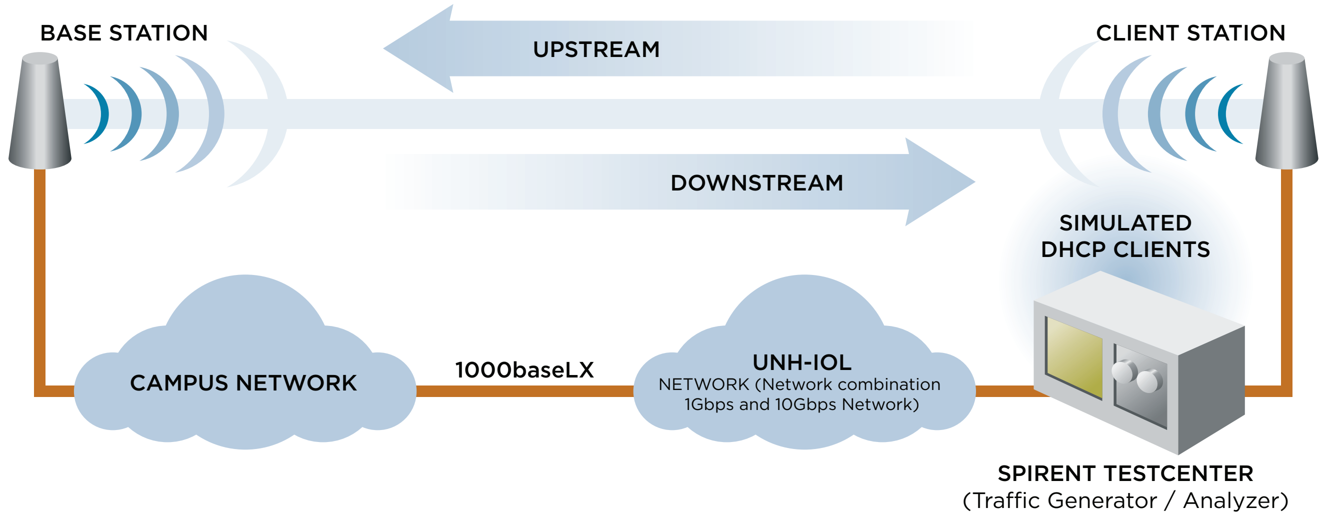
At the Durham Public Library, the signal delivered by the TVWS network was received using an off-the-shelf window-mount antenna commonly used to capture over-the-air digital television signals (image below). The purpose was to evaluate the performance of TVWS connectivity using a low-cost, consumer-grade antenna.



The Durham Public Library installation handed off traffic from the TVWS network to a library Ethernet port, which connected to a dedicated personal computer made available to library patrons.

At the UNH Dimond Library, the TVWS signal was received by an indoor log antenna, which in turn handed off the RF signals to CPE and, via an Ethernet port, to a PC for users to access the Internet via TVWS.

At the UNH IOL, the TVWS signal was received by a log antenna, which connected to CPE and the IOL's test network via an Ethernet port as depicted in the diagram below:



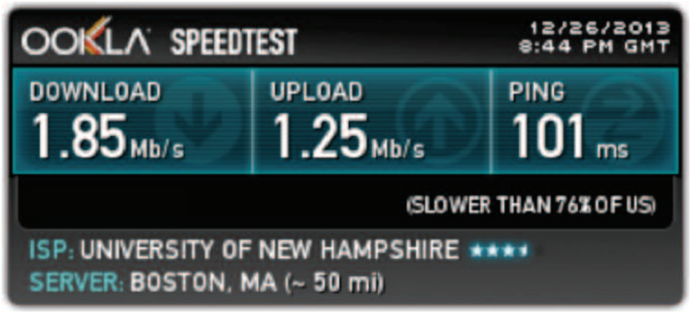
Performance and measurement

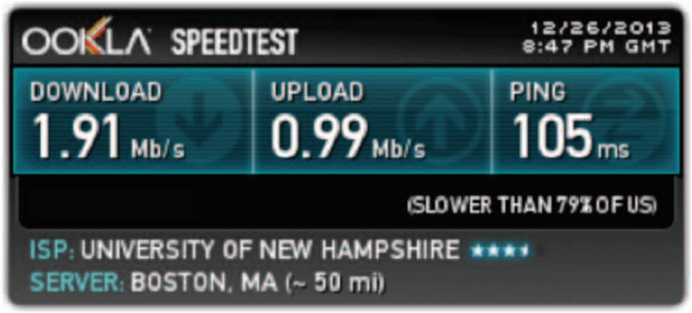
Durham Public Library implementation

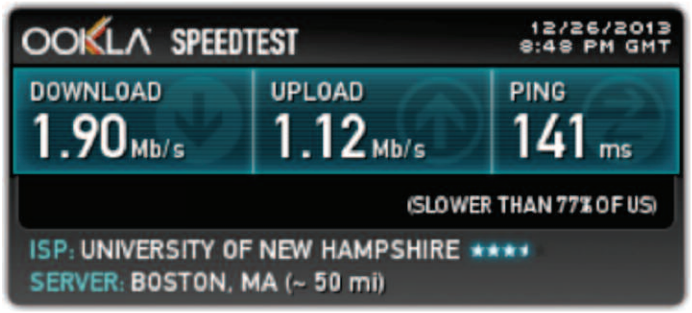
Recorded downstream data rates ranged from sub-megabit speeds to 1.91 Mbps. Upstream performance ranged from 430 kbps to 1.3 Mbps. Modulation in all instances was BPSK.

The lower-end performance measures appear to have been impacted by issues associated with antenna placement; over time, the TVWS network produced more consistent downstream data rates of 1.5 Mbps or higher. Latency ranged from 101 milliseconds to 141 milliseconds. Also, the trial underscored the influence of modulation and error-correction approaches implemented for TVWS. These choices are determined by the weakest reception link within the network — in this case the Durham Public Library, which used a window-mounted antenna that, while convenient and easy to install, compromised performance. Higher performance may have been achievable through the use of a rooftop-mounted log antenna.

Selected performance measurements from Dec. 26, 2013 appear below:





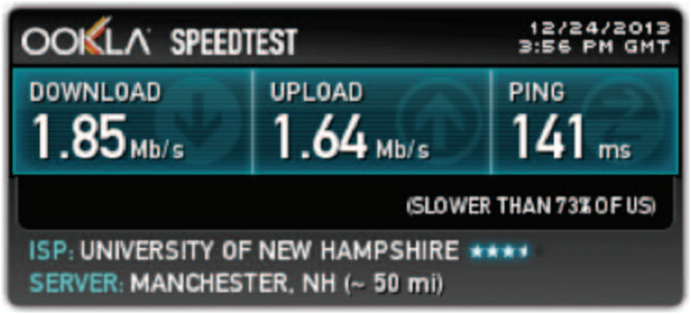


Source: Speedtest.net by Ookla. Images have been edited to remove performance grades.

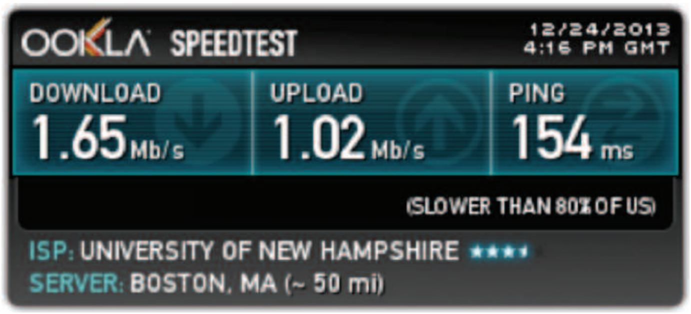
University of New Hampshire Dimond Library implementation

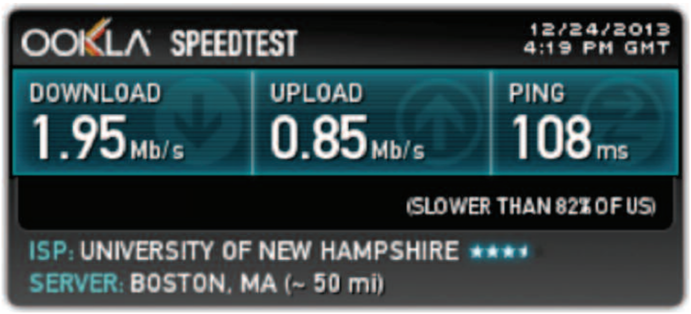
Recorded downstream data rates for two client computers located at the UNH Dimond Library ranged from 790 kbps to 1.95 Mbps using BPSK modulation. Upstream delivery ranged from 440 kbps to 1.64 Mbps. Latency ranged from 107 milliseconds to 154 milliseconds. Selected performance measurements from Dec. 24, 2013 appear below:

Dimond Library Client 1



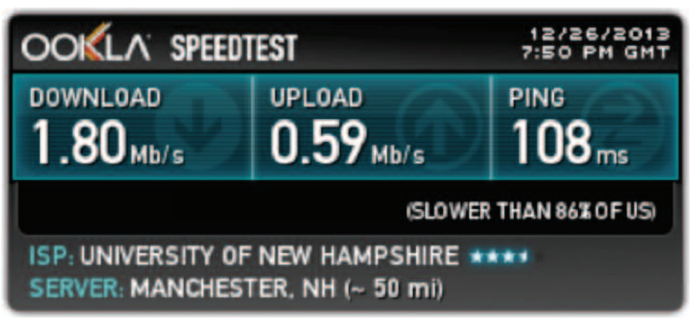
Dimond Library Client 2:

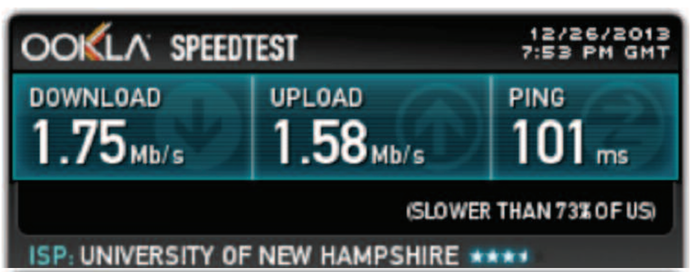


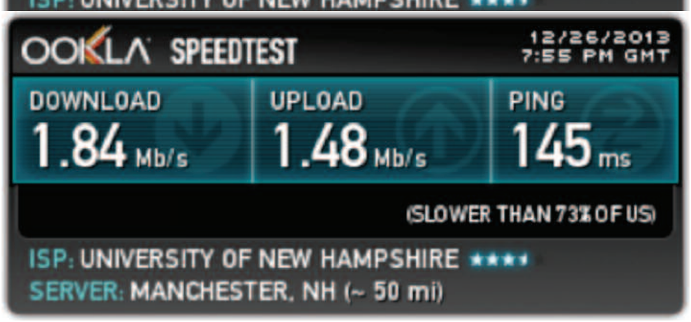


UNH IOL implementation

Recorded downstream data rates exhibited a more consistent range, from 1.75 Mbps to 1.91 Mbps. Upstream performance ranged from 590 kbps to 1.61 Mbps. Modulation again was BPSK. The narrower and improved performance range may have been influenced by the use of an outdoor, roof-mounted antenna. Latency ranged from 108 milliseconds to 161 milliseconds. Selected performance measurements from Dec. 26, 2013 appear below:



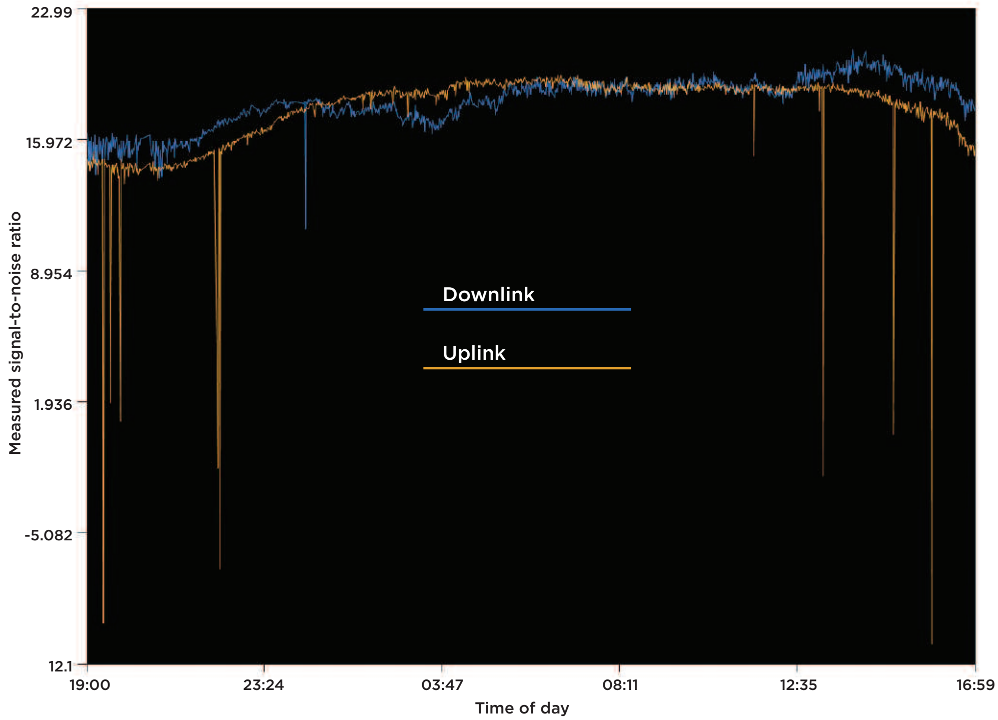




Signal quality

Measurements of signal-to-noise recorded at the UNH IOL indicate generally strong signal quality over the TVWS network. During the TVWS implementation, there was occasional ingress into the band that affected performance as well as measured SNR at all locations, which varied over time.

The graph below shows S/N in decibels for downstream (blue) and upstream (gold) paths over the BCoE TVWS link from Dec. 18-19, 2013.



Lessons learned

In evaluating the UNH BCoE pilot TVWS project from conception to installation to performance and feedback indicators, key takeaways and observations include these findings:

- Deployments must take into account building permit requirements plus historical building variances and other possible restrictions.
- Advance design and analysis is recommended prior to physical installation, with qualified system engineering and installation teams critical to successful implementation.
- A multi-tiered modulation approach is recommended so that locations closer to the base stations may benefit from advanced modulation schemes such as 16QAM, while outlying locations may attain the best performance from lower-order modulation with improved robustness.
- The ability to conduct real-time spectral analysis and automatically assign traffic to available TVWS channels is essential for achieving carrier-class performance.
- Real-time availability of key operational parameters is necessary to optimize antenna positioning and CPE location.
- Similarly, real-time visibility into performance using standard Management Information Bases and Simple Network Management Protocol platforms must be available to optimize base station installation.

Conclusions

Based on UNH BCoE's inaugural field trial of TVWS technology, we observe that:

- TVWS is capable of providing high-quality, high-speed Internet access to locations within distances of approximately 8 km (or roughly 5 miles); however, each installation involves unique characteristics, with the topology of the coverage area rising as the determining factor in terms of performance and reach.
- The installation of TVWS requires a systematic model to enable more scaled deployment.
- TVWS technology available today seems to be best-suited for supplying Internet connectivity within a small community, but appears to be less well-suited for supplying connectivity between communities and into far outlying areas.

Recommendations

Like other TVWS trials, the UNH BCoE deployment in late 2013 demonstrated basic viability of TVWS technology, reflecting the finding that broadband wireless links can operate in the TV band to deliver Internet connectivity at downstream data rates exceeding 1 Mbps without interfering with incumbent TV station signals.

At the same time, UNH BCoE's deployment in Durham, N.H., along with a review of available literature surrounding the TVWS category, underscores that TVWS must overcome current limitations in order to scale such that it may contribute to resolving obstacles BCoE has identified for ubiquitous broadband availability and adoption.

As of early 2014 inexpensive commercial grade equipment is not available to economically support deployments, whether smaller scale rural or large-scale commercial. To spur more investment activity in the technology sector, the economics must support a TVWS model that justifies deployment into any size market segment based on volume expectations of mass-market reach.

One key factor to mass-market deployment is reducing the cost of an end-to-end TVWS system including CPE devices by simplifying the installation, automating system management with standard protocols, integrating the technology into large-scale devices and automating the manufacturing processes.

This concluding section, addressing steps required to achieve global market deployment for TVWS, reflects the experience of the UNH BCoE leadership team in evolving proprietary cable modem technology into a mass-market broadband offering for the worldwide cable telecommunications industry through the creation of standards and the integration of an end-to-end solution that drove CPE costs down dramatically and created critical scale economies for the technology.

Our recommended approach to create a global market deployment of broadband services using TVWS spectrum includes:

Establishing a viable business model

- Enable entrepreneurs to operate successfully as ISPs using TVWS technology.
- Demonstrate the ability to compete in the marketplace with TVWS-enabled services.
- Project and build a multi-year financial model that encourages investment.
- Drive an environment that encourages silicon vendor participation.
- Share success stories that demonstrate how TVWS can profitably deliver broadband Internet access to unserved and underserved areas.

Creating an interoperable environment

- Assure interoperability across all deployed services within the operating environment.
- Allay concerns of RF interference to legacy services with effective description of best practice RF techniques in the specifications, well-documented and rigorous product certification process and education of regulatory bodies.
- Standardize the end-to-end system including back-office systems, enabling an interoperable multivendor environment.
- Provide an open test environment, test equipment, test process and procedures involving industry vendors, university resources such as the UNH IOL and/or other participants that can help speed time to market.
- Enhance future product generations to measure S/N ratio and automatically assign modulation and error correction algorithms to optimize the tradeoff between robustness and performance; and to switch to other available channels to improve S/N performance.

Reducing regulatory uncertainty

- Provide a clear and predictable regulatory path for TVWS access. Investors and technology developers must be able to act with certainty in knowing that adequate amounts of TVWS spectrum will be assured for use by unlicensed devices. In the U.S., even as regulators prepare to reallocate licensed spectrum in the 600 MHz band, it is equally critical to protect and preserve access to unlicensed TVWS spectrum in the broadcast band as a way to spur investment, innovation and improved broadband access.
- Enable strong leadership and governance within existing industry consortia to drive TVWS technology to mass-market deployment.

Refining standards and establishing training programs

- Standardize equipment and operation across vendors and industry.
- Specify CPE devices with ease of installation and operation with “plug and play” technology including automatic compensation for changes in operating environment.
- Reengineer the 802.22 specification to be technically feasible for rural, suburban and urban areas and market as a mass deployment technology.
- Bring IEEE 802.22 specifications in-line with existing specifications where possible to leverage available technology, silicon and products. The operational challenges for cable modems and TVWS are similar in many respects; IEEE 802.22 could better align itself with deployed technology.

- Simplify the IEEE 802.22 requirements for installing CPE devices.
- Provide effective training and educational material for service providers.
- Engage with existing industry organizations to develop training classes and create new jobs for small business specialists that will manage deployment and installations

Report authors and contributors:

Chris Grobicki is an Executive Consultant for YAS Capital Partners and BCoE, with 35 years of experience in the high technology industry. He has worked in engineering development, program management and executive capacities on computer and communication products and was one of the early pioneers of cable modem and DOCSIS® technology.

David Lavallee is an Information Technology Specialist at the University of New Hampshire, responsible for managing and maintaining a 2,500-node network delivering Gigabit Ethernet service to approximately 17,000 clients, along with a 802.11 a/b/g/n wireless service to more than 30,000 devices on campus.

Lincoln Lavoie is Senior Engineer and acts as an industry lead for the executive steering body at the University of New Hampshire InterOperability Laboratory (UNH IOL). He is responsible for the technical management of the broadband access technology groups, including Digital Subscriber Line (DSL), Gigabit Passive Optical Network (GPON), and Technical Report 069 (TR-069).

Paul Nikolich is an Executive Consultant for the Broadband Center of Excellence, responsible for technology and standards. Paul is also an IEEE Fellow and holds a leadership position in the IEEE serving as Chairman of the IEEE 802 LAN/MAN Standards Committee.

Dr. Rouzbeh Yassini is CEO of YAS Capital Partners and acting Executive Director of the University of New Hampshire Broadband Center of Excellence. He is widely regarded as the "father of the cable modem," reflecting his pioneering work in cable broadband technology as the founder and CEO of LANCity, and as a prominent contributor to the CableLabs Data over Cable Services Interface Specification (DOCSIS®).

Editor:

Stewart Schley, Director of Content Development for UNH BCoE and Contributing Analyst for One Touch Intelligence, has been writing about media, technology and business subjects for more than 20 years, for publications including *Multichannel News, CED Magazine* and Kagan World Media.

Endnotes

[i] Dr. Rouzbeh Yassini, “Broadband 2020: Achieving Ubiquity,” November 2013, <http://unhbcoe.org/research/white-papers-and-reports/achieving-ubiquity>, accessed Jan. 8, 2014

[ii] Richard Thanki, “Economic Significance of Licence-Exempt Spectrum to the Future of the Internet,” June 2012, <http://download.microsoft.com/download/A/6/1/A61A8BE8-FD55-480B-A06F-F8AC65479C58/Economic%20Impact%20of%20License%20Exempt%20Spectrum%20-%20Richard%20Thanki.pdf>, accessed Dec. 19, 2013

[iii] United States Federal Communications Commission, “Second Memorandum Opinion and Order,” Sept. 23, 2010 <http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-10-174A1.pdf>, accessed Dec. 12, 2013

[iv] Google, “Spectrum Database Overview,” <https://support.google.com/spectrumdatabase/>, accessed Dec. 3, 2013

[v] Microsoft Corp., “Super Wi-Fi Technologies,” 2012 <http://research.microsoft.com/en-us/projects/spectrum/microsoft-super-wifi-overview.pdf>, accessed Nov. 29, 2013

[vi] Richard Thanki, “Economic Significance of Licence-Exempt Spectrum to the Future of the Internet,” June 2012, <http://download.microsoft.com/download/A/6/1/A61A8BE8-FD55-480B-A06F-F8AC65479C58/Economic%20Impact%20of%20License%20Exempt%20Spectrum%20-%20Richard%20Thanki.pdf>, accessed Dec. 19, 2013

[vii] New Scientist Magazine, “Free broadband via gaps in spectrum gets biggest trial,” Oct. 17, 2013 <http://www.newscientist.com/article/mg22029394.500-free-broadband-via-gaps-in-spectrum-gets-biggest-trial.html#.UqE5xtJDuSo>, accessed Nov. 29, 2013

[viii] Federal Communications Commission, “In the Matter of Unlicensed Operation in the TV Broadcast Bands, Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band, Second Memorandum Opinion and Order,” September 2010. <http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-10-174A1.pdf>, accessed Dec. 4, 2013

For more information, visit

www.unhbcoe.org

Follow BCoE on Twitter: **@UNHBCOE**

Visit BCoE on Facebook:
Facebook.com/UNHBCOE