Institution: University of Bristol

Unit of Assessment: 15 - General Engineering

Title of case study: Wireless LAN - pioneering research underpins standards and improves wireless video performance

1. Summary of the impact (indicative maximum 100 words)

WiFi technologies are integral to our internet-connected lives. Most of the world's wireless data passes over one of the global WiFi standards. For more than 20 years the University's ***Communication Systems & Networks*** (***CS&N***) Group has contributed towards the development of these technologies, and to products that conform to them.

The WiFi standards are vital since they ensure that computers, mobile phones, set-top boxes and tablets all use the same waveforms and protocols to wirelessly connect to the Internet. They ensure inter-operability between different products and manufacturers.

CS&N pioneered the use of multicarrier modulation and multiple antenna (MIMO) technologies. These underpin the current WiFi standards (802.11g/n), ratified in 2003/2009. Research on wireless and video communications led, via spin-out ProVision Communications, to a range of robust wireless-video products for high definition video transmission in the home. These products are now manufactured and sold by Global Invacom.

In partnership with Farncombe, the Group has developed a defacto WiFi test standard. This combines the Group's rigorous WiFi antenna validation & verification measurements with its system level in-home modelling and measurement tools. *[text removed for publication]*. To date, more than five million WiFi routers have benefited from the University's WiFi test process.

2. Underpinning research (indicative maximum 500 words, currently 672 words)

Academics in the University's ***CS&N*** group have been conducting research into Wireless LANs (WLAN) and their numerous applications for more than 20 years. These research activities have directly influenced the latest WiFi standards (802.11g/a/n/ac). A WiFi certified device is a WLAN that conforms to one of the 802.11 standards.

The Group led the radio development in Europe's first wireless network research project (LAURA, 1992-1995) and proposed the modulation and equalisation technologies behind Europe's first high-speed WLAN standard. Beach (UoB since 1987) and Nix (UoB since 1992) led the development of multi-carrier modulation schemes to radically enhance data throughput [1]. To deliver reliable communications at rates in excess of 20Mbps, they also proposed a single carrier waveform with time-domain adaptive equalisation (echo cancellation) [2]. Prior to these contributions WLAN data rates were limited to 1-2Mbps because of echoes in the radio channel.

The Group has made major contributions to the field of electromagnetic ray tracing. The work in [3] is based on Bristol's first indoor ray tracing propagation model. Crucially, our three-dimensional models not only predict accurately the spatial and temporal structure of the radio channel, but also separate the radio channel characteristics from the antenna characteristics. The Group continued to develop internationally recognised ray tracing models for indoor use (WLAN). Nix and Hilton (UoB since 2001) quantified the impact of antenna pattern, polarisation and array geometry by combining WiFi radio simulations with indoor ray tracing and per-element 3D antenna measurements [3]. This work represents the world's first rigorous and scientific approach to the evaluation of WiFi antenna solutions.

The wireless distribution of video reliably around the home is a key requirement of the consumer electronics industry. ***CS&N*** developed the robust wireless transmission technologies and packetisation strategies required to support home video distribution over the emerging WiFi

standards. From 1998 Nix, Bull (UoB since 1992) and Doufexi (UoB since 1998) published numerous papers on the subject of wireless coverage and automatic link speed adaptation (matching the data rate to the quality of the radio channel) from a video streaming perspective. The Group later developed a range of robust wireless video transmission and link adaptation strategies. Previously, WLAN systems treated data and video packets equally, however the Group demonstrated that video packets should be treated differently [4], and indeed pioneered the use of video optimised packetisation and link adaptation technologies.

In 2001, Piechocki (UoB since 1997) and Nix demonstrated the world's first practical multiple-antenna WLAN performance results based on spatial multiplexing (the concurrent transmission of multiple data streams in the same radio spectrum) [5]. This approach was adopted in the 2009 ratified 802.11n standard. The research made use of measured multi-element radio channels using representative antenna systems (rather than mathematically idealised antennas and channels).

In 2001, Doufexi and Nix used their detailed knowledge of the emerging European and US WLAN standards to publish a comparative summary of the two leading proposals [6]. Using the Group's in-house bit level simulators the paper compared the data rates and operating range of each standard. Google Scholar shows that [6] has been cited in more than 460 subsequent publications.

3. References to the research (indicative maximum of six references)

[1] H. Xue, A.R. Nix, M. Beach, et al (8 authors), 1993. *Air interface considerations for wireless LANs*. Proceedings of the IEE 4th European Conference on Radio Relay Systems, Edinburgh, UK, 45-50, ISBN: 0-85296-594-X.

[2] *A.R. Nix, G.E. Athanasiadou and J.P. McGeehan, 1996. *Predicted HIPERLAN Coverage and Outage Performance at 5.2 and 17 GHz using indoor 3-D Ray-Tracing Techniques*. Wireless Personal Communications, 3, 365-388, dx.doi.org/10.1007/BF00461146.

[3] D. Kong, E. Mellios, D. Halls, A. Nix and G. Hilton, 2011. Throughput sensitivity to antenna pattern and orientation in 802.11n networks. IEEE 22nd International Symposium on Personal Indoor and Mobile Radio Communication (PIMRC), dx.doi.org/10.1109/PIMRC.2011.6140078.

[4] *P. Ferre, A. Doufexi, J. Chung-How, A. Nix and D. Bull, 2008. *Robust Video Transmission Over Wireless LANs*. IEEE Transactions on Vehicular Technology, 57(4), 2596-2602, dx.doi.org/10.1109/TVT.2007.909258.

[5] R. Piechocki, P. Fletcher, A. Nix, C. Canagarajah and J. McGeehan, 2001. *Performance evaluation of BLAST-OFDM enhanced Hiperlan/2 using simulated and measured channel data*. IEE Electronics Letters, 37(18), 1137-1139, dx.doi.org/10.1109/TVT.2007.909258.

[6] *A. Doufexi, S. Armour, M. Butler, A. Nix, D. Bull, J. McGeehan and P. Karlsson, 2002. *A comparison of the HIPERLAN/2 and IEEE 802.11a wireless LAN standards*. IEEE Communications Magazine, 40(5), 172-180, dx.doi.org/10.1109/35.1000232.

* References that best indicate the quality of the underpinning research.

4. Details of the impact (indicative maximum 750 words)

The WLAN modulation & coding developments, WiFi multiple antenna algorithms, in-home radiowave propagation models and robust video-over-WiFi strategies reported in section 2 have contributed to global wireless communication standards, led to wealth creation by enabling the development of innovative products and services and improved customer's WiFi experiences in the home. Details of this impact are given in the following subsections.

WLAN Standards

Bristol led the radio development in Europe's first WLAN research project (1992-1995) and was the first university member of the European Technical Standards Institute (ETSI, the European body responsible for radio standardisation). Over the period from 1992-1994, the Bristol group proposed the majority of the modulation and equalisation designs behind Europe's first WLAN standard. This standard (known as Hiperlan) "*was a pivotal activity in the development of one of the most important markets in today's communications industry*" and Bristol researchers *were "major contributors"* [a]. More than 60% of this radio standard (and almost all of the modulation and equalisation) was based directly on the University's research work, for example [1,2]. From 1995 to

1998, the Group continued to develop the multi-carrier WLAN approach first proposed in [1]. The University's Group presented numerous contributions to the ETSI and in 1996 the Hiperlan /2 standard was ratified [a]. Although this standard is no longer in use, "*HIPERLAN did leave a lasting legacy by providing WLAN regulations at 5GHz*" [a] - the University-influenced radio solution was largely adopted for IEEE 802.11a/g/n/ac, which is now used in billions of devices world-wide.

The Bristol team are credited with the publication of the *first* publicly available technical paper to propose the use of multicarrier technology for WLAN applications. *[text removed for publication]*. This paper was presented at a symposium organised by the IEE in October 1993 [1]. *[text removed for publication]*.

In 2008 the WiFi alliance stated that more than 350 million 802.11a/g units had been shipped [c]. In 2013 the WiFi standard provided wireless connectivity in over 2 billion shipped devices. This includes smartphones, tablets and laptops, to TVs, gaming and audio systems [d].

Wireless Video Transmission

The University's research into wireless and video signal processing [4] led to the spin-out company ProVision Communications Ltd, which was founded by Nix and Bull in 2001. By 2009, the company had grown to employ 25 staff and was acquired in 2011 by Global Invacom [e]. By exploiting Bristol's wireless & video patents and technologies, Global Invacom has been able to develop an innovative range of wireless video products for the satellite and cable TV industry [e]. ProVision exploited University research, such as [4,6], to develop the world's first whole-home truly robust wireless HDTV transmission system [e]. The units beamed multi-channel television pictures from a wireless gateway to multiple receivers around the home. Prototype units (marketed as AXAR) were demonstrated at the Consumer Electronics Show 2009/2010 in Las Vegas [f] and the Cable Labs Summer Conference in Colorado, 2010 [e]. Industry feedback, via prototype evaluation, confirmed that the Bristol video and WiFi adaptation algorithms ensured these units were the first to deliver carrier-grade high-definition video around the home using the WiFi standard [e]. As a result, ProVision was awarded the Frost & Sullivan European Innovation Award for WiFi Streaming Technology in 2010 [e]. ProVision's AXAR1500 multi-room wireless video system was cited by an expert panel at the International Broadcasting Conference as one of 2010's top five digital video processing technologies [g]. ProVision also provided the WiFi and video technology, developed by the ***CS&N*** group to enhance spectator experience at the World Rally Championships, *[text removed for publication]* [e].

Exploiting the University's link adaptation and smart packetisation algorithms [4], WiFi antenna designs and video optimisation techniques, the University worked with ProVision to further develop its Consumer Electronics Show demonstrator to produce the world's first whole-home wireless HDMI product [e]. The HDMI units made use of Bristol's advanced WiFi and video bit rate adaptation algorithms [4]. These dynamically adjusted the video quality and bit rate based on regular estimates (tens of times per second) of the link throughput [e]. This intelligent adaptation delivered smooth multi-channel video streaming even in poor channel conditions [e]. Bristol's adaptation was vital in overcoming the data rate fluctuations seen over WiFi links [e]. Global Invacom acquired ProVision in 2012 and took the University technology underpinning the wireless-video demonstrations to create a wireless high definition video sender. This product was launched in 2012 [e] and can be purchased via, for example, Amazon [h].

Antenna Optimisation and WiFi Performance Verification

In 2011, the University's ***CS&N*** group worked with BSkyB to optimise the RF and MIMO antenna system on their latest WiFi-enabled Hub. Ray modelling was combined with antenna optimisation [3] to ensure that their integrated MIMO antennas gave near-optimal performance when enclosed in the product casing [i]. BSkyB launched their Sky Hub in October 2012, claiming "*unbeatable WiFi performance*". BSkyB now supply this Hub to all of their UK broadband subscribers, which currently totals more than 4.2 million users [i].

In partnership with Farncombe [e], Nix and Hilton have developed a defacto WiFi test standard that addresses the core market need to verify and validate the WiFi performance of new products [j]. The approach combines the Group's work [3] in 1) WiFi antenna design, integration and

verification, 2) in-home propagation modelling (ray tracing) and 3) real-world multi-antenna WLAN throughput evaluation. Using this new process, the Group began working with Virgin Media to ensure that their recently launched Super Hub became "*the best-in-class WiFi router for cost/performance and quality of service*" [k]. ***CS&N*** applied their innovative WiFi test processes to optimise the antenna locations and orientations within the casing of the new Super Hub to maximise WiFi coverage and data rate within the home [3]. The Head of Quality at Virgin Media said "*the resulting benchmarking gave us critical information on performance of the antenna design, positioning and its connection to the WiFi chipset that has resulted in the best-in-class WiFi router*" [k]. The Group also performed competitor evaluations that formed part of Virgin Media's new Super Hub launch material. Virgin launched the device to its 4.3 million UK subscribers in May 2013 and publicly announced Bristol's support via a press release [l]. *[text removed for publication]* [k].

In 2013, the ***CS&N*** group analysed and evaluated five new wireless products for BSkyB, *[text removed for publication]* [i]. *[text removed for publication]*.

In recognition of Bristol's "*pioneering contributions to the Wi-Fi standards from the early 1990s, and also their world-leading research in Wi-Fi antenna design and characterisation*", Broadcom (the world's largest supplier of WiFi chipsets) donated six sets of reference 802.11 hardware flashed with their internal firmware [c]. Access to this software has not been offered to any other university [c]. The software provides low-level control not normally available to the public [c]. *[text removed for publication]*.

5. Sources to corroborate the impact (indicative maximum of 10 references)

[a] Owner, Discrete Time Communications
[b] *[text removed for publication]*.
[c] European Technical Director, Broadcom.
[d] Qualcomm webpage *WLAN Technology*.
[e] VP Business Development, Global Invacom Ltd
[f] The Telegraph article *CES 2010: Watch Sky on your laptop anywhere in the home*, January 2010.
[g] http://www.electronicspecifier.com, news article *ProVision wireless HDTV system makes 2010's best digital video technology short list*, August 2010.
[h] Amazon online shop *Provision Wireless HD Sender*, downloaded in 2013.
[i] RF Design Engineer, BSkyB.
[j] http://www.v-net.tv news article *Farncombe offers WiFi testing service; Virgin Media is first customer*, June 2013.
[k] Head of Quality CPE, Virgin Media.
[l] Virgin Media press release *Virgin Media launches fastest wireless hub in the UK*, May 2013.