Institution: University of Aberdeen		
Unit of Assessment: 12 (Engineering)		
Title of case study: [IC5] Internet Engineering research impacting standards and guidelines, benefiting equipment vendors, network operators and Internet users' experience		
Period when the underpinning research was undertaken: 2009-2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Professor Gorry Fairhurst	Professor; PI	01/1988-present
Dr Raffaello Secchi	Lecturer; Co-I	06/2010-present
Period when the claimed impact occurred: 2014 - 2020		
Is this case study continued from a case study submitted in 2014? N		

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

Research conducted at the University of Aberdeen has contributed new algorithms and protocols, measurement analysis, and architectural design to Internet Standards published by the Internet Engineering Task Force (IETF). Since 2015, the research team has published 11 specifications in the Requests for Comments (RFC) series. These are the key working documents underpinning the Internet, which have been and are being implemented by the networking industry, informing the current practice of Internet operators. Fairhurst's RFCs are now deployed globally in products from companies such as Google and Apple.

2. Underpinning research (indicative maximum 500 words)

In 2020, the Internet supports over 4,500,000,000 users worldwide. The day-to-day operation of the Internet depends on voluntary adherence of vendors and operators to standard protocols and procedures specified by the Internet Engineering Task Force (IETF). Research in Internet Engineering at the University of Aberdeen led by Prof. Gorry Fairhurst and the wider team (Dr Raffaello Secchi and Research Assistants Tom Jones and Ana Custura), has focussed on addressing key Internet Engineering challenges and played a fundamental role in enhancing the efficiency of Internet systems through collaborations in projects [P1-P7] with partners across the EU. Their work spans the design of Internet equipment, measurement of Internet infrastructure, to the design of the protocols that control data transport across Internet paths.

Evolving the Internet Transport System and defining a new Transport Interface [P3] [P4]

Working with key industry partners including Mozilla, CISCO and Celerway, research led by Fairhurst [P3] underpinned the design of a new architecture for the transport system. [1] This addressed two key obstacles faced by Internet innovators by 1) lowering the barrier to application development through a new open transport system, that allows developers to automatically select a suitable protocol for an Internet application and to specify the options required; and 2) providing an architectural change where new transport services can seamlessly be integrated. The new approach introduced by Fairhurst, decouples the transport service from the design of the underlying transport protocol. This eliminates previous obstacles to deploying new methods, enabling evolution within the transport system, and allowing developers to benefit from new methods wherever they become available. The NEAT Project [P3] proposed a new system architecture and contributed this to the IETF. An Open Source research implementation demonstrated the feasibility of this approach. [1] Fairhurst and his team implemented the Datagram subsystem, and then defined the interaction with the network layer [P4], resulting in further standards contributions.

Reducing End-to-End Internet Latency across the Internet Path [P2]

Between 2012 and 2015, research in the interaction of transport and network protocols by Fairhurst, [P2] performed an in-depth analysis of the end-to-end delay experienced by Internet users. [2] This work brought Internet latency to the fore as an important performance metric. Latency measures the time needed to transport packets across the network, which ultimately impacts download speed and responsiveness of time critical communications.

In collaboration with industry partners, Fairhurst and Secchi explored the performance of Active Queue Management (AQM) methods and showed these can significantly reduce latency, without requiring investment in higher speed communications links. [2] Explicit Congestion Notification (ECN) methods were defined that enable a router to better control the latency it introduces, resulting in the design of a new congestion control algorithm, TCP Alternative Backoff with ECN (ABE). [3] Presentation of this method won the Best Paper Prize at IFIP Networking, 2017, and was contributed to the IETF (RFC8511).

Determining Appropriate Sending Behaviour for Internet Datagrams [P1-P4] [P6-P7]

From 2015-2018, and building on research around the User Datagram Protocol (UDP), [P1] Fairhurst explored the impact of the industry move towards UDP transport [P4] by focusing on how network operators balance operational needs and user privacy concerns, to understand the implications of encryption on manageability of network traffic ($1) resulting in contributions to the IETF transport working group [$2].

Fairhurst and his team designed new research tools enabling large-scale Internet measurement of [P4]. These were used to examine and report the path transparency of transport protocol headers in the mobile and wired Internet (e.g., [4-6]). Employing these tools new large-scale measurements by Fairhurst's team provided "*invaluable engineering reality checks*", [$3] needed to progress UDP specifications and for the IETF to select codepoints, which are used by routers and switches to give traffic priority levels, and for the lower-effort service designed to support safe background download of software updates and data. [$3] Fairhurst built on earlier experience from research exploring a less than best effort Internet service for rural inclusion [P1].

In 2018, following analysis of path failure due to packet size [P3] [5], Fairhurst and his team worked with the University of Muenster to co-design a new technique, Datagram Packetization Layer PMTU Discovery, DPLPMTUD. This can automatically determine when it is safe to increase the size of packet being used, which allows a sender to detect a black hole and reduce the packet size (when current methods could fail by using full-sized packets [5]). DPLPMTUD successfully avoids packet size black holes for 99.72% of tested IPv4 Internet paths. Using larger packets can reduce the packet rate by 17%, for 96% of paths, compared to using a default size of 1280B. Operating at the transport layer, the new technique supports all current protocols, including transport methods that use encryption.

As part of an on-going project, initiated in 2018, Fairhurst and his team, funded by the European Space Agency (ESA) [P6] [P7] analysed QUIC, an encrypted UDP transport, originally proposed by Google to accelerate web sessions. This research proposed changes to the QUIC acknowledgment strategy, [7] and use of ECN. These and other topics were proposed by Fairhurst and his team as ways to ensure acceptable performance of the emerging IETF QUIC protocol over broadband satellite systems.

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

References

[1] Khademi, **Fairhurst, G**, Jones, T., et al., NEAT: *A Platform- And Protocol-Independent Internet Transport API*, IEEE Commun. Magazine, vol. 5, no. 6, pp. 46-54. DOI: https://DOI.ORG/10.1109/MCOM.2017.1601052, 2017.
This paper denotes underpinning research in evolving the Internet transport system.

[2] Briscoe, B, **Fairhurst, G** et al., *Reducing Internet Latency: A Survey of Techniques and their Merit*, IEEE Commun. Surveys & Tutorials, vol. 18, no. 3, pp. 2149 - 2196. DOI: https://DOI.ORG/10.1109/COMST.2014.2375213, 2014.

This paper underpinning research identifies key methods to reduce Internet latency.

[3] Khademi, **Fairhurst, G.** et al, *Alternative Backoff: Achieving Low Latency and High Throughput with ECN and AQM*, IFIP Networking, Stockholm, S. Best Paper Prize. DOI: 10.23919/IFIPNetworking.2017.8264863, 2017.

This paper denotes transport research that reduces end-to-end Internet latency.

[4] Custura, A, **Secchi, R & Fairhurst**, **G**, *Exploring DSCP modification pathologies in the Internet*, Computer Commun. vol. 127, pp. 86-94. DOI: https://DOI.ORG/10.1016/J.COMCOM.2018.05.016, 2018.

This paper describes underpinning research in determining safe use of DSCPs.

[5] Custura, A., **Fairhurst, G.** & Learmonth, I., *Exploring usable Path MTU in the Internet, Network Traffic Measurement and Analysis Conference*, Vienna, A. DOI: https://DOI.ORG/10.23919/TMA.2018.8506538, 2018

This paper describes research to increase the packet size used across internet paths.

[6] Raffaele Zullo R, Jones T, **Fairhurst G**, *Overcoming the Sorrows of the Young UDP Options*, Network Traffic Measurement and Analysis Conference, On-Line, 2020 DOI: https://doi.org/10.23919/TMA.2019.8784601.

This paper describes research on the path transparency of UDP transport packets.

[7] Custura, A., **Fairhurst, G.** & Jones, T. *Rethinking ACKs at the Transport Layer*, IEEE/IFIP Networking: Future Internet Technologies https://bit.ly/3llYoyB, Paris, June 2020.

This paper denotes underpinning research in the design of transport acknowledgement.

Grants

[P1] UKRI dot.rural Digital Economy Research Hub, EPSRC EP/G066051/1(10/2009-09/2015) http://bit.ly/36Hi2RM (GBP11, 814, 897) (Coordinator: Aberdeen University).

[P2] RITE (Reducing Internet Transport Latency, EU FP7-ICT 317700 (11/2012-10/2015; EUR5,000,000) https://bit.ly/3d5JsSp (8 partners, Aberdeen portion: GBP371,270.00) (Coordinator: SRL, NO)

[P3] NEAT (A New, Evolutive API and Transport-Layer Architecture for the Internet), EU 644334 (03/2015-02/2018; EUR4,000,000) http://bit.ly/3ntWCh0 (8 partners, Aberdeen portion: GBP344,925.00) (Coordinator: SRL, NO)

[P4] MAMI (Measurement and Architecture for a Middleboxed Internet) European Commission, EU IC 688421 (01/2016-02/2018; EUR3,000,000), https://bit.ly/2HXfnZE (8 partners, Aberdeen portion: GBP306,249) (Coordinator: ETH, Zurich, CH)

[P5] PREC (Prioritisation and Resilience for Emergency Communications), EU MONROE FIRE, (06/2016-06/2018) https://bit.ly/3ln5tPv (GBP114,522) (Coordinator: SRL, NO)

[P6] QUIC Standardisation Support, ESA (2018-19) (GBP52,493) (University of Aberdeen)

[P7] Mitigation Techniques for addressing the impact of Latency over Satellite Networks (MTails), ESA ARTES-4 (02/2020-09/2021) http://bit.ly/3ixYvp2, (GBP98,332) (Coordinator: Indra, ES)

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

The IETF is the primary Internet Standards Development Organisation (SDO). Its mission is to make the Internet work better by producing high quality relevant technical documents that influence the way people design, use, and manage the Internet. An open standards policy combines contributions from industry (such as Apple, Microsoft, Google, Ericsson), network operators (such as BT, Google, Akamai), leading research institutions (as in this case study) and other stakeholders, to provide the technical and operational expertise required to develop standards and industry Best Current Practice (BCP). BCP documents are published in the Request For Comments (RFC) series and can be accessed online from www.ietf.org/standards/rfcs. Fairhurst chairs the Transport area working group (TSVWG) and has co-authored 11 RFCs across the Internet and Transport areas since 2014 (total 273 pages), totalling 28 since 2002 (with 183 citations in other RFCs) [$2].

RFC specifications are crucial to the day-to-day running and expansion of the Internet. Although the commercial gain yielded by such open standards is not measurable, these standards are widely used at all stages in Internet service delivery: by networking equipment designers, by network and service operators, in data centres and as a basis for enterprise. RFCs are also used as the basis for government procurement of equipment and services, and underpin other standardisation, including cellular mobile standards for 5G technology.

Evolving the Internet Transport System and defining a new Transport Interface [P3] [P4]
Specifications: *RFC8095; RFC8304.*

Research by Fairhurst directly contributed to formation of the IETF Transport and Services (TAPS) standards working group in 2014 [$6]. Work contributed by NEAT [P3] underpinned standards work that unifies the interface between the Internet transport system and applications [$7]. In 2015, Fairhurst and Welzl (University of Oslo) were invited to present this work at the Internet Architecture Board SEMI Workshop, which set future directions for a series of IETF standards. Fairhurst's research provided an "*important first step*" [$6] and has continued to be a "*key contributor*" to the TAPS architectural framework [$7] (as a contributor to the first 3 published documents and a co-author of RFC8095 and RFC8304). He is a co-author of two further working group standardisation documents [$6].

Operating system developers, such as Apple Computer, [$7] can immediately benefit from the new TAPS specifications. An Internet Technologies Engineer at Apple stated, "*In 2018, Apple released Network.framework at the World Wide Developer Conference… The architecture produced by the TAPS working group deeply informed the development of this framework. Since its release, many applications have adopted this framework on iOS and macOS*" [$7]. This has provided developers with a common secure framework across different platforms, enabling each application to automatically tune the transport system to the current network conditions. The new interface also simplifies development of applications and products. In another example, Celerway Communications is using the automated methods defined by TAPS to enhance the proxy functionality in its software to boost the throughput of mobile applications [$4].

Reducing End-to-End Internet Latency across the Internet Path [P2]
Specifications: *RFC7567; RFC8087; RFC8511.*

Research led by Fairhurst and Secchi in AQM techniques [P2] underpinned an Internet BCP in 2015, RFC7567, co-authored by F. Baker (Cisco) and Fairhurst. [$3] Operators are benefitting from this BCP when configuring AQM routers to meet the demands of new low-latency Internet applications. This was followed by RFC8087, identifying the additional benefits of using ECN with AQM (co-authored by Fairhurst and Welzl). Both AQM and ECN techniques are important in reaching the demanding latency targets of 5G mobile networks, which the GSM Association predicts will be up to 50 times lower than networks using 4G.

Fairhurst and his research team collaborated with the University of Oslo and Netflix to develop a standard based on their ABE method, [4] published as RFC8511 [$2]. In 2018, Fairhurst and Secchi continued to contribute to the next generation ECN techniques being standardized in the IETF as L4S (Low Latency, Low Loss, Scalable Throughput) [$9]. Fairhurst also served on the scientific advisory board of the Swedish READY (Research Environment for Advancing Low Latency Internet) Project, which applied Internet techniques (including ECN) to a range of industry problems.

Determining Appropriate Sending Behaviour for Internet Datagrams [P1-P4] [P6-P7]
Specifications: *RFC8085; RFC8084; RFC8899.*

Internet Engineering research resulted in new transport methods and guidelines for Internet Best Current Practice for application and protocol designers. This includes co-authoring guidelines for using UDP as an Internet Transport, RFC8085. This is BCP148 (replacing RFC5405, its predecessor, also co-authored by Fairhurst and cited by 59 RFCs [$2]).

There is a growing volume of encrypted UDP Internet traffic, as a result of increased concern about privacy and a desire for a faster pace of protocol evolution. This has required the Internet community to consider the implications of pervasive encryption. Fairhurst (with a team from ETH, Zurich and Vijay Gurbani, USA) organised an industry summit to bring together key researchers, Internet engineers and network equipment vendors from across the world, to examine how to meet the challenges posed by encrypted traffic, resulting in an industry whitepaper [$1]. Current IETF standards work (co-authored by Fairhurst) will articulate these challenges in an informational document [$9] describing Transport Header Confidentiality, Network Operations, and the Evolution of Internet Transport Protocols [$2].

Research results by Fairhurst and his team provided "*careful and insightful input*" in the standardization of RFC8210, a core IPv6 specification. [$8] The research provided a "*key input to the development*" [$7] of a new standard: DPLPMTUD, RFC8899. This makes a significant design change that allows developers of transport systems to avoid reliance on network-layer fragmentation and enables an application to safely increase the size of packets that it sends [$8]. Development within the FreeBSD Project [$10] added DPLPMTUD to the Stream Control Transport Protocol (SCTP), a core transport protocol used in cellular mobile Internet [$5].

Based on research [P3] and [P6], Fairhurst worked within the standards process to contribute to the design for IETF QUIC, and proposed and analysed extensions [P7] to the standard. The IETF QUIC standard includes DPLPMTUD, normatively referencing RFC8899 [$5]. QUIC is expected to have significant take-up by companies, and is already 35% of Google's traffic in April 2020, and a growing component of total Internet traffic (about 7%), expected to increase as companies add support to their products after IETF standardisation in 2021.

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

[$1] Industry workshop to develop a position on Challenges in Network Management of Encrypted Traffic, https://arxiv.org/abs/1810.09272, 2018.
[$2] Contributor information for G. Fairhurst, IETF Data Tracker, http://bit.ly/3d698OC.
[$3] Letter from a Senior Distinguished Engineer in the Office of the Chief Technology Officer (CTO), Dell-EMC, describing contributions of the authors to IETF standards.
[$4] Letter from Cellerway Communications, describing collaboration to develop the IETF TAPS specifications, and their exploitation by Cellerway in products.
[$5] Letter from a Master Researcher at Ericsson Research describing standards contributions for DPLPMTUD and the relevance to the SCTP and QUIC Transports.
[$6] Letter from an Engineering Manager at Akamai Technologies, describing contributions of the authors and the research underpinning development of the TAPS specifications.
[$7] Letter from Apple Computer, describing contributions of the authors and resulting use by the TAPS specifications in commercial products.
[$8] Letter from a Check Point Fellow at Check Point Software, describing the contributions of the authors and resulting use of the DPLPMTUD specifications.
[$9] Active work in the Transport Area Working Group, http://bit.ly/30DS8uo, 2020.
[$10] BSD Journal Article explaining how FreeBSD is being used to drive forward standards, highlighting contribution by the authors, http://bit.ly/2Gxvtc4, p35-39, 2020.