Institution: University of Cambridge		
Unit of Assessment: UoA10		
Title of case study: Improving mobile phone and network performance through multipath routing and rate control		
Period when the underpinning research was undertaken: 2000-2005		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s): Professor Frank Kelly	**Role(s) (e.g. job title):** Professor of the Mathematics of Systems at the Faculty of Mathematics	**Period(s) employed by submitting HEI:** 1990 – October 2018
Period when the claimed impact occurred: September 2013 – July 2020		
Is this case study continued from a case study submitted in 2014? Yes		

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

With increased demands on the internet, Kelly developed at the University of Cambridge a novel multipath extension to Transmission Control Protocol (TCP), the main system of rules for transferring data across the internet. His algorithm has been translated into a practical implementation, "Multipath TCP" (MPTCP), standardised by the Internet Engineering Task Force, the international body for defining internet operating protocols.

Key impacts:

[I1] In the current REF period MPTCP has been deployed on over 1,380,000,000 Apple iPhones worldwide, representing sales of over USD951,000,000,000, and is also used on Korea Telecom and Huawei smartphones.

[I2] In 2015 a new company was founded, Tessares, which uses MPTCP to provide faster internet services, particularly in rural areas, in six countries. Tessares employs nearly 30 people.

[I3] Since July 2020, MPTCP is a standard feature of 5G.

2. Underpinning research (indicative maximum 500 words)

Background

All traffic on the internet (downloads, videos, etc.) is broken down into, and transferred as, packets. These packets contain information about the source and the destination. Transmission Control Protocol (TCP) is the main system of rules for transferring these packets across the internet.

In the late 1990s, Professor Frank Kelly CBE FRS developed at the University of Cambridge a conceptual mathematical framework, which elegantly described packet-switched networks, such as the internet. His foundational theory demonstrated that TCP effectively solves a very large-scale resource allocation problem, and that it is both stable and fair.

Research within REF Period at the University of Cambridge

In 2000 and 2003, Kelly **[R1]** and **[R2]** helped show the generality and range of applicability of the conceptual framework in an era of rapidly growing communications capacity. He explained why the internet worked as well as it did, providing confidence in its reliability and robustness under rapid growth, and rendering re-design unnecessary.

This work has been extremely influential in the networking community, and provided the foundation of future internet research, evidenced by his international awards listed below.

With increased demands on the internet, in 2005 Kelly **[R3]** developed a novel algorithm to route traffic *via* multiple paths that increases reliability and performance, without compromising stability. His algorithm is a routing extension to TCP. He constructed a fluid-flow (differential equation) model describing which path (route) should be used, and how much traffic (rate control) should be sent.

TCP is an acknowledgement-based system; once a packet arrives safely, an acknowledgement is sent to the sender. The time that elapses between the sending of a packet and receipt of acknowledgment is known as the Round-Trip Time (RTT). Initially, it appeared to be very hard to stabilise a system sending traffic over multiple paths with RTTs potentially differing by several orders of magnitude.

However, Kelly's insight is twofold:
Firstly, you only need to know about congestion on the route you are looking at, which makes it simpler, and less demanding, when looking at RTTs of different orders of magnitude. His sufficient condition for local stability is decentralised as the responsiveness of each route is constrained by the RTT of that route, and not RTTs of other routes on the network, even between the same source-destination pairs.

Secondly, in the conceptual "Open Systems Interconnection" (OSI) model of the internet, there are seven defined "layers", each of which is responsible for a different protocol. TCP operates at the transport layer. Kelly's contribution was to show that routing choice and congestion control are part of the same problem, and therefore, routing allocation should be integrated with flow control at the transport (i.e., the same) layer. This is why his form of multipath capability is a "direct-drop" in replacement for TCP, as it takes place at the same layer and does not require modification of any of the layers above or below.

Subsequently, a group of computer science researchers translated Kelly's theoretical work on routing traffic via multiple paths into a practical implementation, "Multipath TCP" (MPTCP). Since REF 2014, MPTCP has had extensive reach and significance. It has been deployed in iPhones and other mobile phones, increased internet speed in 6 countries and was recently adopted as part of 5G developments.

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

[R1] Models for a self-managed Internet, Frank P. Kelly, Philosophical Transactions of the Royal Society A 358 (2000) 2335-2348, DOI: 10.1098/rsta.2000.0651.

[R2] Fairness and stability of end-to-end congestion control, Frank Kelly, European Journal of Control 9 (2003) 159-176, DOI: 10.3166/ejc.9.159-176.

[R3] Stability of end-to-end algorithms for joint routing and rate control, Frank Kelly and Thomas Voice. Computer Communication Review, 35(2) (2005) 5-12. DOI: 10.1145/1064413.1064415.

The papers listed above are all published in peer-reviewed journals.

Evidence of the quality of the research – selected international prizes and awards

2005 IEEE Koji Kobayashi Computers and Communications Award. *"Kelly's critical insight into the performance and behavior of telecommunications networks and his application of the economic theory of pricing to congestion control and fair resource allocation have reshaped how researchers study future directions for the Internet."*

2015 IEEE Alexander Graham Bell Medal "*for exceptional contributions to the advancement of communication sciences and engineering". "For creating principled mathematical foundations for the design and analysis of congestion control, routing, and blocking in modern communication networks."*

4. Details of the impact (indicative maximum 750 words)
Kelly's novel multipath extension to Transmission Control Protocol (TCP), the main system of rules for transferring data across the internet, increases reliability and performance without compromising stability.

An EU project, "Trilogy", involving a former PhD student of Kelly's (Damon Wischik), UCL, and international collaborators drew on Kelly's pioneering work at the University of Cambridge and translated it into a practical specification, "Multipath TCP" (MPTCP). Due to Kelly's key insight that routing and rate control should take place at the same layer, MPTCP is a direct "drop-in" replacement for TCP rather than a major re-design of the Internet.

MPTCP provides lower latency (quicker responses), faster data transfer, and improved resilience to traffic surges and link failures than TCP. It thus greatly improves user experience of demanding Internet applications such as video streaming and speech recognition (for example, Apple Siri).

Having been an Internet Draft since 2009, the Internet Engineering Task Force (IETF) – the international body that defines standard Internet operating protocols – published the MPTCP specification as a Proposed Standard on 30 March 2020 **[E1]**, and it was added to the Internet Assigned Numbers Authority (IANA) on 3 April 2020.

> *"MPTCP is one of the most successful new IETF protocols…[and] has been very widely deployed."*
> Principal Researcher, BT Applied Research and joint IETF MPTCP Working Group Chair **[E2]**.

MPTCP is implemented in iOS, MacOS, and the Linux kernel. Some known deployments, since August 2013, are described below.

[I1] Improving smartphone performance

At the 2017 **Apple** Worldwide Developers Conference, an annual showcase typically attracting 6,000 software developers, Apple announced they had been using MPTCP for Siri – Apple's digital assistant – since 18 September 2013 (iOS version 7) *"with great results"* **[E3]**.

Siri uses MPTCP to switch seamlessly between Wi-Fi and cellular networks, even when users are moving, to significantly improve performance. The time it takes for a user to see the first spoken word appear on screen is

> *"20% faster in the 95th percentile",* and *"5x reduction in network failures"* are seen, compared with normal TCP.
> Apple Senior Software Engineer **[E3].**

Since 16 September 2015 (iOS version 9), Apple's "Wi-Fi Assist" has used MPTCP to automatically switch between Wi-Fi and cellular networks, enabling iPhones to stay connected even in weak reception **[E3]**.

In response to demand, Apple made MPTCP's Application Programming Interface available for iOS developers' widespread use on 19 September 2017 (iOS version 11) **[E4].** Due to Siri's improved user experience, Apple enabled MPTCP for Apple Maps and Music on 19 September 2019 (iOS version 13) **[E3]**.

[Text removed for publication] **[E5].**

Between 29 September 2013 and 27 June 2020, Apple reported iPhone sales figures of USD951,675,000,000 (06-2020), corresponding to at least 1,381,814,000 iPhone users benefiting from MPTCP worldwide **[E6].**

In Asia, **KT Corporation** (South Korea's largest telephone company) implemented MPTCP, known as "GiGA LTE", in high-end Samsung and LG smartphones for premium users in June 2015. By combining traditional LTE (Long-Term Evolution) – a standard for wireless broadband communication for mobile devices – with local Wi-Fi networks,

> *"GiGA LTE ensures a 1.17-Gbps speed, about 15 times faster than the speed of existing LTE services."*

Korea Economic Daily, 24 February 2016 **[E7]**.

KT Corporation has exported GiGA LTE to Turkey's **Türk Telekom** (2016), which has 18 million wireless subscribers; Thailand's largest mobile phone operator, **Advanced Info Service** (2017) which services 51% of the country's population; **Botswana Fibre Networks Ltd** (2017), and in 2018 signed an MoU with German-based **albis-elcon [E7]**.

Independently, **Huawei** developed "Link Turbo", implementing MPTCP to enable simultaneous LTE and Wi-Fi access, and multipath UDP (User Datagram Protocol, an alternative transmission protocol). This was deployed on Honor V20, a brand flagship product, in January 2019 [text removed for publication] **[E8].**

[I2] Enabling faster internet

Smartphones are not MPTCP's only application. In March 2015, Université Catholique (UC) de Louvain – one of the key Trilogy partners – launched a spin-off company, Tessares, which employs nearly 30 people **[E9]**. Partnering with Proximus, Belgium's largest telecommunications company, Tessares developed an innovative technology, Hybrid Access Networks, standardised by the Broadband Forum (a non-profit industry consortium) in May 2019 **[E10]**. These networks use MPTCP to combine xDSL (wired) and LTE (wireless), providing higher bandwidth (faster Internet) services in rural areas, where xDSL performance is poor and have been introduced in six countries, including the Netherlands and Finland. Few figures are publicly available, however, in the Netherlands, 150,000 customers benefit from a speed improvement of less than 30Mbps to at least 50Mbps **[E9]**, whilst,

> *"Hybrid Broadband [offering speeds up to 100Mpbs] will make surfing the web easier for more than one million Finnish households [representing over 18% of the population]."*

Broadband Service Business Manager, Telia Finland **[E9]**.

Two quarters after launching Tessares' technology, Telia Finland's broadband customers grew by 15,000 (+3%), and the Average revenue per user increased by 10% since the previous quarter **[E9]**.

> *"[MPTCP] leverages Kelly's theoretical results and makes them usable… on the Internet." "Five different countries [Belgium, Croatia, Finland, Lithuania, Netherlands – and, since the letter, Malta] benefit from this technology and there are ongoing discussions with network operators in Asia Pacific and America."*

Tessares' Managing Director **[E9]**.

[I3] Selected for 5G

With increased demand for mobile broadband, 3GPP (3rd Generation Partnership Project, uniting seven standards organisations from Asia, Europe, and North America) made MPTCP a standard feature for 5G, Release 16. This was included in 3GPP's draft technical specification, 24.193 V0.3.0, in September 2019, and released on 3 July 2020 **[E11].**

MPTCP won the 2019 SIGCOMM Networking Systems Award **[E12]**, for *"significant impact on the world of computer networking"*.

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

[E1] RFC 8684 (formerly RFC 6824) *"TCP Extensions for Multipath Operation with Multiple Addresses".* Authors: Handley (UCL, Trilogy partner) and co-authors Ford, Raiciu (formerly UCL), Bonaventure (UC Louvain, Trilogy partner), Paasch (Apple). Published as Proposed Standard 30 March 2020.

[E2] Testimonial from the Chair of the IETF MPTCP Working Group, 23 January 2020.

[E3] Slides and transcript from Dr Christoph Paasch's (Apple Senior Software Engineer) presentations *"Advances in Networking"* at the 2017 and 2019 Apple Worldwide Developers Conference, WWDC17 5-9 June 2017 and WWDC19 3-8 June 2019, (see p40 and 75-80).

[E4] Apple's online documentation explicitly citing RFC 6824 "*Use Multipath TCP to create backup connections for iOS"* (page published 4 August 2017), and *"Improving Network Reliability Using Multipath TCP",* both webpages accessed 1 July 2019.

[E5] Confidential.

[E6] iPhone sales data aggregated from 2014-2019 and Q1-Q3 2020 (pp. 26, 129, 239, 311, 352, and 395) from Apple Inc. Annual Reports. Where different sales values are reported in 2017 and 2018 (due to a change in accounting) the lower figures have been taken. Since September 2018, Apple no longer publicly report unit iPhone sales, so for 2019 and 2020 the average unit value of an iPhone in 2018 has been used to conservatively calculate unit sales.

[E7] *KT's GiGA LTE*. KT presentation at the IETF MPTCP Working Group meeting, 21 July 2015. *"KT Exports "GiGA LTE" to Turkey"*, The Korea Economic Daily, 24 February 2016. *"KT to Provide 1 GiGA LTE Solutions to Thailand, Botswana"*, Business Korea, 29 August 2017. *"albis-elcon and KT sign MoU on 'GiGA Technology' cooperation"*, albis-elcon newsletter, 12 July 2018. Webpages accessed 1 July 2019.

[E8] Huawei presentation and confidential letter.

[E9] Articles from Tessares' Newsroom: *"KPN Banks on Hybrid Access Tech to Retain Rural Subs",* Broadband World News, 16 December 2019; "*Telia Finland Boosts Internet Speed with Hybrid Broadband",* 19 October 2018; and *"More reach of OTT video services."* Testimonial from Tessares' Managing Director, 14 June 2019.

[E10] Broadband Forum Technical Report TR-378 *Nodal Requirements for Hybrid Access Broadband Networks*. Issue: 1 Issue Date: May 2019. See p31 for the main advantages of MPTCP-based Hybrid Access.

[E11] MPTCP: Opening the way for convergence in the 5G era, Tessares White Paper, Nicolas Men and Olivier Bonaventure, 14 March 2019. 3rd Generation Partnership Project; Technical Specification Group Core Network and Terminals; Access Traffic Steering, Switching and Splitting; Stage 3 (Release 16), 3 July 2020, see p34 of pdf document.

[E12] SIGCOMM Networking Systems Award, *"2019: Multipath TCP implementation in the Linux kernel",* webpage accessed 1 July 2019.