Institution: University College London		
Unit of Assessment: 11 - Computer Science and Informatics		
Title of case study: Improving Data Transfer with Multipath Transmission Control Protocols		
Period when the underpinning research was undertaken: 2010 - 13		
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:**
Mark Handley	Professor of Networked Systems	2003 - 2020
Period when the claimed impact occurred: 2013 - 2020		
Is this case study continued from a case study submitted in 2014? Y		

1. Summary of the impact

Research at UCL pioneered the suite of Multipath Transmission Control Protocols (MPTCP). These protocols improve the efficiency of data transfer across the Internet when compared to the classic suite of transfer protocols “TCP/IP”. The UCL team demonstrated the improved effectiveness of these protocols which has led to multiple commercial deployments, either by Internet Service Providers or by companies such as phone handset suppliers. In addition, UCL research has been incorporated into Operating Systems such as Apple’s iOS and Linux and it is now shaping the design of 5G cellular networks. As a result of UCL research, millions of users benefit every day from smoother transitions between different Internet connections ensuring that online services have a much higher performance and reliability.

2. Underpinning research

The Transmission Control Protocol, which accounts for the vast majority of all Internet traffic, allows users to transfer packets of data between two IP addresses. The TCP/IP “suite” of protocols for data transfer is fundamental to the architecture of the Internet. However, since the development of devices able to connect in multiple ways, such as phones that can transmit over Wi-Fi or cellular networks, the use of a single pathway for transmission has limited improvements in transfer speed and efficiency.

Research into Multipath Transmission Control Protocols (MPTCP) by the team at UCL has helped to address this issue. They have developed ways to transfer files between two IP addresses across multiple “subflows”. These subflows allow for a device to move between connections more smoothly or even to use multiple paths simultaneously. Previously, when a phone, for example, disconnected from a Wi-Fi network, it would not have simultaneously been using its cellular signal to transmit data; this causes an interruption to the transmission, sometimes impeding the function of apps. The same interruption could also happen when a new Wi-Fi connection was joined. Now, instead, a phone using MPTCP can transmit data using both pathways. The data transfer can now also migrate over to whichever pathway is more efficient, resulting in a better experience for the user.

Research by Professor Handley and his team at UCL was crucial to the development of these new protocols. In a 2011 paper, in collaboration with other scholars, the team at UCL demonstrated the challenges which would need to be overcome to enable MPTCP to be attached on to the existing Internet architecture (**R1**). This research looked at the behaviour of middleboxes (networking devices which filter or inspect data packets). By studying 142 access networks in 24 countries, they showed that issues with middlebox behaviour would interfere with data transmission in ways that would limit the extension of TCP. The measurement results in this paper guided the design of MPTCP.

The team at UCL also developed an algorithm to optimize MPTCP, preventing congestion in the transfer of data (**R2**). Implementing the algorithm in Linux, they were able to demonstrate the increased efficiency of MPTCP as compared to TCP. They produced further work on the principles for functioning MPTCP, taking into account the various challenges to its implementation (**R3**). They also demonstrated the efficiency gains of MPTCP in datacentres (**R4**). Because datacentres have multiple pathways to transmit within their stacks, they can transmit data using MPTCP, allowing for speedier transfer across multiple routes. By running MPTCP on Amazon's cloud computing service, Amazon EC2, they were able to demonstrate that MPTCP outperforms TCP by a factor of three.

The results of this work were taken up by the Internet Engineering Task Force (IETF, the main standards organization for the Internet). A working group was formed to standardize MPTCP. The team at UCL authored three Request for Comments (RFCs). These are standards documents for the IETF, defining MPTCP and establishing guidelines for its use (**R5, R6**). These guidelines have been promoted from the experimental track at the IETF to the standardisation track. This means that individuals who are both developing products and designing deployments commercially, can use MPTCP to help shape the future of the Internet.

3. References to the research

R1. Honda M, Nishida Y, Raiciu C, Greenhalgh A, **Handley M**, Tokuda H. (2011) Is it still possible to extend TCP? Proceedings of the ACM Internet Measurement Workshop 2011. 198 citations
https://dl.acm.org/doi/10.1145/2068816.2068834

R2. Wischik D, Raiciu C, Greenhalgh A, **Handley M.** (2011). Design, Implementation and Evaluation of Congestion Control for Multipath TCP. Proceedings of the 8th Usenix symposium on Networked Systems design and implementation NSDI 2011, 437 citations
https://dl.acm.org/doi/10.5555/1972457.1972468

R3. Raiciu C, Paasch C, Barre S, Ford A, Honda M, Duchene F, Bonaventure O, **Handley M.** How hard can it be? designing and implementing a deployable multipath TCP. 9th USENIX Symposium on Networked Systems Design and Implementation NSDI 12. 353 citations
https://www.usenix.org/system/files/conference/nsdi12/nsdi12-final125.pdf

R4. Raiciu C, Barre S, Pluntke C, Greenhalgh A, Wischik D, **Handley M.** (2012) Improving datacenter performance and robustness with multipath TCP. Proceedings of the ACM SIGCOMM 2012 conference on Applications, technologies, architectures, and protocols for computer communication, 530 citations https://doi.org/10.1145/2018436.2018467

R5. Ford A, Raiciu C, **Handley M**, Barre S. (2011) Iyengar J. Architectural Guidelines for Multipath TCP Development. RFC 6182, 2011, 532 citations. https://tools.ietf.org/html/rfc6182

R6. Ford A, Raiciu C, **Handley M**, Bonaventure O. (2013) TCP Extensions for Multipath Operation with Multiple Addresses". RFC 6824, 2013, 713 citations
https://tools.ietf.org/html/rfc6824

4. Details of the impact

As a result of UCL research, its widespread dissemination (over 3,000 citations), and its uptake by the IETF, Prof Handley and team have helped to ensure a faster, smoother, more connected Internet globally. MPTCP is of growing importance to the telecoms industry and its customers. A search on Google patents for "MPTCP" currently lists 1,380 patents granted, with many more applied for. The team's work has informed the practices of many technology companies, and improved the experiences of millions of users:

- Operating systems, such as Apple's iOS and Linux, have incorporated MPTCP.
- The team at UCL has been involved in collaborations with service providers and handset makers, such as Korean Telecom and Samsung, helping to provide faster Internet.
- The research has allowed companies such as Tessares to provide more efficient Wi-Fi services in rural areas.
- MPTCP is also an important feature of 5G networks, helping to improve connectivity around the world.

In 2019, Mark Handley was awarded a Sigcomm award *"For fundamental contributions to Internet multimedia, multicast, congestion control, and multi-path networks, and the standardization of Internet protocols in these domains"* (**S1**). His work has had a vital impact on the Internet's ongoing transformation.

Impact on Apple iOS and its users

In 2013, Apple incorporated MPTCP in iOS 7, shipping it from Linux into its own software, after consulting UCL research published in (**R6**). Their initial use case was the voice activated Siri assistant (**S2**). Siri sends audio samples from the user's query to Apple's servers and returns the answer. It is crucial that this exchange happens without delay, but an iPhone cannot know in advance whether its Wi-Fi link or its cellular link will work best. MPTCP allows iOS to try both. The phone can then rapidly migrate to the link that works best at that instant. According to Apple, MPTCP reduces the delay before the first word of the response by 20% and eliminates 80% of failed connections. Based on their experience with Siri, Apple introduced Wi-Fi Assist in iOS 9 (released on 16 September 2015), which allowed apps such as Safari to benefit from the transition between subflows thanks to MPTCP. Apple enabled MPTCP for all applications on iOS 11, meaning app designers can now make use of MPTCP to optimise their functionality. As of 2019, Apple has incorporated MPTCP into their Apple Maps application and their streaming service (**S2**). Apple's Networking Architect Christoph Paasch says that, as a result, users "*are seeing much less music streaming stalls*" (**S2**). Apple also enabled MPTCP on MacOS from MacOS 10.10 onwards. According to Apple, over 800 million devices run an MPTCP-capable version of iOS or MacOS, meaning all users of those devices now benefit from the improved data transfer enabled by MPTCP.

Impact of MPTCP on other telecoms services

Linux Kernel: MPTCP is now incorporated into the mainline Linux kernel (as of release 5.8, in August 2020), so is available for use in Android and Linux servers. Much of this work was performed by Intel (**S3**).

Korean Telecom and Samsung: In 2015, Korean Telecom (KT) teamed up with Samsung to launch a commercial MPTCP proxy service called Giga LTE. Giga LTE makes use of MPTCP to dramatically improve wireless performance. Samsung shipped an Android port of the Linux MPTCP implementation on Samsung S6 and S6 Edge devices sold in Korea. KT deployed proxy servers in their production network using the Linux MPTCP implementation. Together, these can be used to harness the power of Wi-Fi and phone signals at the same time. When a user selects "Giga LTE" on their phone, MPTCP is enabled for all applications. Connections then use both LTE and Wi-Fi to connect to servers on the Internet. Because of the MPTCP congestion control algorithm, rather than simply splitting dataflows equally between the two pathways, the Samsung phones can use all the available power. KT reported in 2015 that this could improve performance significantly. Their published results are included in the news article about Giga LTE (**S4**).

<u>**Tessares**</u>: Tessares, based in Belgium, is pursuing the proxy approach to deploying MPTCP, informed by the research of the UCL team (**S5**). Their target market is home or small business networks. In some areas, especially in rural locations, Internet services are delivered by ADSL at speeds slower than can be achieved over the faster LTE service, but LTE bandwidth may be

scarce at busy times, and is often much more expensive. By deploying MPTCP proxies in the customer's home or office router and in the telecom's network, MPTCP can preferentially use ADSL, but when high bandwidth is required and LTE capacity is available, MPTCP can use both networks simultaneously to improve performance. Proximus, Belgium's largest mobile provider, deployed Tessares MPTCP solution in 2016 in Frasnes-Lez-Anvaing, and (as of 2017) is planning a larger scale pilot (**S5**). A similar approach has been used by Tessares in collaboration with Croatia's Hrvatski Telecom, to bring faster Internet services to users in rural Croatia. Standards for MPTCP proxies are now being developed in the IETF (**S5**).

Impact on the development of 5G
MPTCP is now in the main 5G network system architecture specification, *3GPP TS 23.501,* released in 2016 (**S6**). This specification, issued by the overarching standards body for telecommunications protocols, the 3GPP, governs the design and implementation of 5G around the world. The new generation of mobile data networks will use MPTCP to ensure low latency (i.e. minimal delays in the transfer of data). The 3GPP has named the technology ATSSS (Access, Traffic Steering, Switch and Splitting). ATSSS was defined in collaboration with various telecoms companies, including KT, Apple, Deutsche Telekom, Orange, and Cisco. ATSSS will allow for seamless transition between 5G and Wi-Fi, or the use of both 5G and Wi-Fi to maximise speeds. MPTCP "*will play a key role in efficiently combining Wi-Fi and 5G"* (**S7**).

KT announced on 28 August, 2019 that it had completed the world's first "5G low latency multi-radio access technology" test in a 5G commercial network in collaboration with Tessares. According to Tessares, "*ATSSS technology reduces the initial session setup time to achieve 5G ultra-low latency in a multi-radio context, resulting in a setup delay of less than half compared to previous approaches"* (**S8**). The use of ATSSS has been described as a key "*differentiator*", one of the crucial differences between 5G and previous generations of cellular networks (**S8**).

In addition, MPTCP informs other solutions within 5G architecture. As the IETF Network working group pointed out in 2018: "One of the key features of 5G…is dual connectivity (DC). With DC, a 5G device can be served by two different base stations. DC will play an essential role in leveraging the benefit of 5G…MPTCP could be integrated with DC and the 5G protocol stack (**S7**). The research into MPTCP by the UCL team has changed networking architecture and will continue to do so during the 5G rollout.

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

S1. 2019 Sigcomm Award for Mark Handley http://www.sigcomm.org/awards/sigcomm-awards

S2. Discussions of Apple's use of MPTCP
- Christoph Paasch (Apple Network Architect) talking about MPTCP at WWDC 2019. https://developer.apple.com/videos/play/wwdc2019/712/?time=3166
- Apple's Support page explaining the uses of MPTCP https://support.apple.com/en-us/HT201373
- A blog explaining how MPTCP is useful for Apple music. http://blog.multipath-tcp.org/blog/html/2019/10/27/apple_music_on_ios13_uses_multipath_tcp_through_load_balancers.html
- A blog discussing Apple's use of MPTCP https://www.tessares.net/apples-mptcp-story-so-far/

S3**.** A discussion of the Linux Kernel and MPTCP
https://www.tessares.net/a-key-step-for-mptcp-integration-in-linux-5-x/

S4. Korean Telecoms and Samsung
- A discussion of KT's collaboration with handset manufacturers to implement MPTCP for giga LTE
https://www.ietf.org/proceedings/93/slides/slides-93-mptcp-3.pdf

- A news article on the development of Giga LTE using MPTCP "KT's GiGA LTE, World's First Commercial Wireless 1 Giga (3-band CA + GiGA WiFi)" https://www.netmanias.com/en/post/korea_ict_news/7591/kt-korea-lte-mptcp-wi-fi/kt-s-giga-lte-world-s-first-commercial-wireless-1-giga-3-band-ca-giga-wifi

S5. Tessares Press releases on their own work with proxy servers

- https://www.tessares.net/
- A discussion of Tessares work in rural Belgium http://tessares.pr.co/154032-tessares-proximus-access-bonding-offering-faster-internet-in-the-rural-areas-now-successfully-qualified-to-move-to-a-countrywide-deplo

S6**.** 3GPP Technical Specification 23.501 (Section 4.2.10 specifies how MPTCP is used for ATSSS (Access Traffic Steering, Switching, Splitting) within the 5G network.) https://www.3gpp.org/ftp/Specs/archive/23_series/23.501/

S7. A report by the IETF networking task force on the implications of MPTCP for 5G. https://tools.ietf.org/id/draft-defoy-mptcp-considerations-for-5g-01.html

S8. A press release discussing KT's development of MPTCP for use on 5G networks. https://tessares.pr.co/181810-kt-tessares-successfully-test-5g-low-latency-multi-radio-access-technology-in-a-commercial-5g-network